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PERMAFROST - CLIMATE ACTIVITIES WITHIN THE CANADIAN CLIMATE CENTRE

by

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ATMOSPHERIC ENVIRONMENT SERVICE

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A publication of the Canadian Climate Program

Abstract

Several stations have been installed to monitor soil temperatures and meteorological parameters in the discontinuous permafrost zone across Northern Canada. These stations record data on an hourly or daily basis, and store the data for retrieval every 3 to 6 months. A preliminary analysis of the data is presented.

Plusieurs stations ont été installées pour contrôler les températures du sol et paramètres météorologiques dans la zone discontinue du gel en permanence située dans le nord du Canada. Ces stations enregistrent des données journalières ou horaires et ces données sont récupérées à chaque 3 ou 6 mois. Une analyse préliminaire de ces données est présentée.

1 Introduction 1
1.1 On Permafrost 1
1.2 Background 4
1.3 Objectives 6
2 Approach 7
2.1 Station Installation 7
2.2 Station Locations 8
2.2.1 Selection Process 8
2.2.2 Schefferville, Quebec 8
2.2.3 Norman Wells, NWT 9
2.2.4 Churchill, Manitoba 10
2.2.5 Mayo, Yukon 11
3 Stations & Data 11
3.1 Description of Stations 11
3.1.1 Schefferville 11
3.1.2 Norman Wells 15
3.1.3 Churchill 17
3.1.4 Mayo 18
3.1.5 Station Data Summary 20
3.2 Data Sampling and Instrumentation 21
3.3 Problems 25
4 Analysis 27
4.1 Overview 27
4.2 The Software 27
4.3 Graphs 28
4.4 Quasi-Thermal Diffusivities 29
4.5 Numerical Heat Flow Model 31

5 Discussion and Recommendations 32

6 References 34

List of Figures

Fig.	Description
1	Distribution of permafrost in the Northern Hemisphere
2a	Ground thermal regime in permafrost
2b	Permafrost thickness in northern Canada
3	Change in permafrost table following vegetation clearing
4a	Active layer response to changes in surface temperature
4b	Permafrost responses to changes in surface temperature
5	Ground temperature profiles
6	Monitoring site locations
7a	Mean annual ground temperatures (Mackenzie Valley)
7b	Churchill ground temperature data
8a	Schefferville: topographical map
8b	Schefferville: air photo
9-13	Schefferville: ground site photos
13b	Environmental hut
14	Climate graph: Schefferville A
15	Norman Wells: topographical map
16	Normal Wells: instrument plan for site EMR-84-2a
17	Canyon Creek: air photo
18	Canyon Creek: air photo
19-20	Canyon Creek: ground site photos
21	Climate graph: Norman Wells A
22a	Churchill: topographical map
22b	Churchill: air photo

23-26 Churchill: ground site photos

27 Climate graph: Churchill A

28 Mayo: topographical map

29 Mayo: site location map

30 Climate graph: Mayo A

31-32 Mayo: air photos

33-34 Mayo: ground site photos

35-39 Temperature graphs

40 Ground temperature response to surface warming

41 Ground temperature response to surface warming

1 Introduction

1.1 On Permafrost

Permafrost, or perennially frozen ground, is defined as the thermal condition of soil or rock, where temperatures exist below 0C over at least two consecutive winters and the intervening summer. About one-half of Canada and 26% of the landmass of the world is underlain by permafrost (fig. 1).

Spatially, permafrost is divided into 4 zones, these being subsea, continuous, discontinuous and alpine. Subsea permafrost is generally relic, the memory of a cold climate prior to submergence. Alpine permafrost results from the colder air temperatures present at higher elevations. Discontinuous and continuous permafrost are controlled primarily by climate, present and past, (increasingly cold air temperatures with higher latitudes), and secondarily by a variety of other factors discussed below. Between them there is, in fact, no well-defined boundary; it is a gradual transition from the seasonally frozen ground in the south to the permanently frozen ground in the north. However, the southern limit of continuous permafrost approximately coincides with the -8.5 C mean annual air temperature, while the southern limit of discontinuous permafrost approximately coincides with the -1.0 C mean annual air temperature (Smith, 1986).

Water or ice content is not necessary for permafrost to exist; however, it is this content which makes the existence of permafrost significant; the different mechanical and thermal properties of water and ice can have a great impact on both the landscape and human construction.

Vertically, the thermal regime is controlled by the upward flux of geothermal heat (from below) and by the ground surface temperature at the top, the surface temperature being more important. Figure 2a (Hardy Assoc., 1984) illustrates an idealized equilibrium thermal regime. The thickness of the permafrost is defined by the below freezing layer between the 0 C isotherm. Figure 2b (Taylor and Judge, 1979) shows how permafrost thicknesses vary across northern Canada.

The ground surface temperature, determined by the surface energy balance, is controlled by many factors, such as air temperature, snow cover, precipitation, vegetation and surface albedo. A conceptual model of the permafrost-climate system is fully discussed in Smith (1986). Horizontal heat flows can exist as well, due to such factors as spatial variations of surface vegetation and albedo, subsurface water flows and slope aspect changes. These would have the effect of putting 'kinks' into the idealized lines shown in figure 2a. Other temperature gradient changes might be caused by temporal changes in the boundary conditions at the top or the bottom, causing a 'pulse' of heat (or cold) through the system. Soil surface temperature

alterations would be caused by any modification of the surface energy budget, such as changes in vegetation (figure 3, Linell, 1973), construction or climatic change. It is with climatic change that this report is concerned.

Figures 4a and 4b (Hardy Assoc., 1984) illustrate changes in the permafrost distribution and the active layer in response to a climatic warming. Figure 4a shows the 'old' and 'new' equilibrium profiles, while figure 4b shows how the profile would change through time, from the 'old' to the 'new' equilibrium state. It is worth noting that such idealized equilibrium states virtually never exist. Climate is not constant, and therefore the upper boundary condition is in a constant state of flux on a variety of time scales.

The disequilibrium resulting from a changing upper boundary condition near the 0 C freezing temperature is the cause of some of the discontinuous permafrost, it being relic. Other areas of discontinuous permafrost result from marginal causal conditions, when spatial variations in such factors as microclimate, slope aspect, soil moisture or surface albedo are the controlling factors in determining the presence of ground surface temperatures below 0 C. Near-surface ground temperatures (i.e. the top of permafrost) are very sensitive to spatial variations of such surface features. This is illustrated by figure 5, which shows the variation in a number of temperature profiles taken from Timmins 4 Permafrost Experimental Site, about 20 km NW of

Schefferville, Quebec (Nicholson and Granberg, 1973). This sensitivity, combined with the complexity of the conceptual model make the study of permafrost-climate relationships a very challenging field.

1.2 Background

An increasing amount of attention has become focussed on permafrost in recent years. Working groups have put forth a variety of recommendations, including long-term monitoring and the development of numerical models for application to permafrost problems (NRC, 1983). A good summary report (NRC, 1983) is included in appendix 1.

Deep soil temperatures can be useful as a source of proxy data for the reconstruction of past climates. In theory, a real-time monitoring program could be used to detect current climate trends. However, there are two problems with detection.

The first is that in order to detect hemispheric or global warming, a geographically extensive (preferably global) data collection network is required. This was not feasible, as drilling holes is quite expensive and the existing network is limited. The second is that permafrost is sensitive to many variables, climatic and otherwise, and that it would be a non-trivial problem to isolate a climatic temperature signal from

the 'noise'. It is certainly not clear that geothermal data collected would be superior to the meteorological data network with respect to detecting climatic change. The advantage of permafrost is that it acts as a filter to the atmospheric signal, smoothing out the noise and eliminating the high frequencies. Unfortunately, other 'noise' is introduced; the response of permafrost to other parameters besides air temperature, such as snow depth, subsurface water flow and varying surface albedo due to terrain type and vegetation variations.

Climate models, on the other hand, are predicting very large changes in our climate within the next 50 to 70 years (Schlesinger, 1986). Although, perhaps fortunately, ice-rich sensitive areas are somewhat buffered from a warming due to the thermal inertia of ice, substantial impacts can be expected to occur. The precise nature of the impacts is unclear, since "most (if not all) of the linkages are poorly known" (Smith, 1986), but will involve such processes as slope movements, creep and relaxation effects, ice wedge cracking and thermokarsting.

It was therefore proposed by AES that some of the climate aspects of the permafrost problem, specifically with regard to anticipated future warming, be addressed. This project was approved by the Panel on Energy Research and Development (PERD), which provided funding for several years of subsequent work.

This report describes the permafrost-climate work undertaken by the Arctic Section of the Canadian Climate Centre as a result.

1.3 Objectives

A March, 1984 report prepared at AES' request by Hardy Assoc. Ltd., entitled 'The Warming Impact of CO2 on Permafrost Distribution", summarizes some of the expected impacts of climatic warming on permafrost, and provided a set of recommendations for the project. Based upon portions of this report, the following objectives were defined:

1. To set up several stations which would monitor permafrost temperatures as well as on-site meteorological variables, it being recognized that permafrost is very sensitive to microclimate. These data collection sites would be in relatively undisturbed areas, and would run untended for periods of months. The data collected would form a set of base-line data which could be used to better understand the nature of permafrost-climate relationships. The stations would be operated for a period of about 10 years.

2. To study possible changes to the permafrost regime of Canada in response to climatic warming, through the use of empirical modelling.

3. To develop a numerical heat flow model which could be used, along with climate scenarios, as a further impact study tool.

2 Approach

2.1 Station Installation

A contract was awarded to Dr. Hardy Granberg (McGill University) to set up the stations. Installations were performed jointly by Dr. Granberg and AES staff. Two stations were set up in the winter of 84/85 (Schefferville and Norman Wells), and one in the fall of 85/86 (Churchill). A description of the installations are given in Granberg (1985a, 1985b). Figure 6 shows the locations of these sites. A more detailed description follows in section 3.

A second contract in 85/86 was let to Carleton University (Prof. M. Smith) to instrument and collect data at Mayo, Yukon. A description of this installation is given in Smith and Burn (1986).

Data from Schefferville are collected under contract by the McGill Subarctic Research Station. Data from Churchill and Norman Wells are collected by local AES staff. Each station is visited annually by a CCC representative for station maintenance.

The collected data are sent to the Canadian Climate Centre, Downsview for quality control, archiving and analysis.

2.2 Station Locations

2.2.1 Selection Process

One of the recommendations of Hardy Assoc. was that the monitoring network be spread across a variety of geographical and climatological regions throughout Canada. This provides a more useful and flexible data-base which could be used for model validation over a broad range of conditions. Various practical aspects had also to considered, such as ease of access and logistical support. A number of experts were consulted with regard to selecting the locations.

2.2.2 Schefferville, Quebec

An extensive amount of permafrost research has been done at Schefferville over the past 20 years. This is because a considerable amount of mining was carried out there, and permafrost was a great hindrance to it. It is probable that the difficulties and high cost inherent in mining in a region underlain with permafrost is a primary reason why the Iron Ore Co. of Canada (IOC) decided to end their operations at

Schefferville (Granberg, personal communication). The research was primarily carried out by people from the Iron Ore Co. of Canada, and the McGill Subarctic Research Station. A summary of this research is documented by Granberg et al. (1983). Many of the thermocouple strings used in the research are still operating, with many years of data having been recorded from them. The McGill Subarctic Research Station is still active, and available for logistics support; thus this area, as far as site location is concerned, was considered ideal from every point of view, both scientific and practical.

2.2.3 Norman Wells, NWT

From an impact point of view, the Mackenzie Valley pipeline corridor has a special importance. The construction of a pipeline is a multi-hundreds of million dollar project with a life span of several decades (a time scale in which climatic change could become significant). Degradation of the pipeline has potentially serious consequences for local contamination of the environment. This pipeline is located in a region of discontinuous permafrost, sensitive to changes in ground surface temperature. Figure 7a (Mackay, 1975) illustrates the marginality of the permafrost in that area. Mackay (1975) suggested that "Some of the numerous recently active thaw lakes in the upper Mackenzie Valley may be a response to climatic change." Further permafrost amelioration could result in significant impacts.

The Department of Energy, Mines and Resources (EMR) is conducting permafrost research in that region, and thus it was possible to 'piggyback' on their efforts. Some of the thermocables they have set up are quite accessible, thereby simplifying set-up and maintenance. A site near Canyon Creek , about 16 km southeast of Norman Wells (fig. 15) was selected as the best available site for our purposes. EMR continues to monitor the cable logged by AES, as well as other nearby sites, thus providing a useful comparison. As well, the climate data collected there will be beneficial to other site specific studies being conducted at Canyon Creek.

2.2.4 Churchill, Manitoba

Some permafrost related research has gone on at Churchill, and an old but still working cable, originally installed by Roger Brown in Sept. 1973 (Hank Johnston, personal communication) was instrumented . GSC has been taking occasional readings of the cable, so a data history exists (table 1, plotted in fig. 7b). It is located on airport property, thus logistics are quite simple. There is an AES observing station at the airport, and the open nature of the thermocable site minimizes local effects which would make airport data non-representative; as a result minimal meteorological instrumentation is required at the thermocable site. Also there is a source of reliable manpower

(the AES presentation staff) who are able to perform station maintenance and data collection.

2.2.5 Mayo, Yukon

Carleton University (Prof. M. Smith) had instrumented a series of shallow cables near Mayo, Yukon. These cables are 5 m deep, and are located near enough to the Mayo observing station so that its data are fairly representative. It was thought that it would be useful to have readings from a number of holes within a fairly small region as opposed to one deeper hole only, as exists at the other locations. This would provide a measure of spatial variability. Most of these holes are read manually once per month, but dataloggers reading daily values have been installed at two of the sites.

3 Stations & Data

3.1 Description of Stations

3.1.1 Schefferville

The station at Schefferville is located at thermocable #16 at the Ferriman permafrost experimental site some 8 km southwest of the townsite. Details of this site may be found in Granberg et al,

(1983) and Granberg et al (1984). These reports contain details on the topographic and geological setting in the form of stereophotographs and maps and also contain drill records from the drilling of the thermocable hole. Papers and reports dealing with the Ferriman site are also included in these reports. Thermocable site #16 at Ferriman is a wind-swept ridge-crest location which, according to thermocable measurements is one of the sites with the lowest ground temperatures found in the Schefferville area. The geographical coordinates of the site are approximately 54 degrees 48 minutes North and 66 degrees 55 minutes West. Its elevation is 593 m ASL. The vegetation is sparse and consists of lichens with some low-grown woody plants within a general setting of Alpine Tundra.

Permafrost conditions at the site and in the general area have been documented by Granberg et al (1983; 1984) and references contained in these reports. The depth of permafrost at cable 16 is unknown, but is probably greater than 100 m.

Figure 8a is a topographical map showing the position of the site (indicated by a filled-in circle). Note the hilly terrain (also visible on the air photo shown in figure 8b), oriented on a northwest to southeast axis. Figures 9 to 13 are photographs taken at the site, showing the local terrain. The bottom photo in fig. 9 shows a nearby mining pit and distant lakes. The hut in which the datalogger is housed can be seen in the bottom photo of fig. 11 and fig. 13a. Figure 13b shows a schematic of the hut,

which is similar to the ones at Churchill and Norman Wells. Figure 14 is a time series graph of climate data taken from the nearby observing site in the town of Schefferville. Note that this is a cold area, with a mean annual temperature of -4.8 C. This area tends to get quite a lot of snow, averaging 398.4 cm/year, however the permafrost site is located on the crest of a hill, and the resulting windiness tends to blow off the snow. Since 1967 there appears to be an upward trend in snowfall, although not in rainfall which averages about 400 mm/year. Mean annual temperatures showed a gradual cooling from 1949 to 1972 followed by a subsequent warming.

Weather conditions at Scheffervile are severe from the point of view of operation of meteorological instruments. Blowing snow with winds of over 100 km/hr may occur. Freezing rain, drizzle and fog occur commonly in early winter depositing glaze, at times more than 5 cm thick and rime occasionally more than 20 cm thick. Winter temperatures below -30 C occur commonly from December to April with extreme lows of -40 to -50 C. Precipitation is usually accompanied by strong winds which make the measurement of both snowfall and rainfall difficult.

Monthly climate data were used to derive the statistics plotted in fig. 14. The top four line graphs plot temperature data. The filled-in circles connected by solid lines represent mean annual temperature, and their values are indicated on the top part of the right hand axis. These data points were

smoothed using a running five-year Gaussian Mean, and these smoothed values are represented by the filled-in boxes connected by heavy dashed lines. The max and min curves represent the maximum and minimum values observed in the data (that is, the warmest and coldest mean monthly temperature for that year). They are represented by open circles connected by dashed lines. Their values can be read off the upper left hand axis. On the bottom part of the chart, precipitation is plotted. The vertical bars represent total precipitation for the year (in mm). The solid circles connected by solid lines represent the total rainfall for the year. The values of these two parameters are indicated on the lower right hand axis. The solid squares connected by heavy dashed lines represent the five-year Gaussian Mean of total precipitation. Snowfall is plotted using open circles connected by dashed lines. Its values are indicated on the lower left hand axis. The values on the bottom of the graph represent mean annual temperature over the period of record and its standard deviation, the mean of the coldest and warmest months, the mean rain, snow and total precipitation.

3.1.2 Norman Wells

The Norman Wells site is known as cable 84-2A-T4 in the designation used by EMR who installed the cable. It is situated some 300 m northwest of Canyon Creek along the Norman Wells-Zama Lake pipeline corridor, about 10 m southwest of the pipeline clearing.

The vegetation of the site is open, dwarfed, black spruce forest with some paper birch and an undergrowth of lichens. The site is underlain by permafrost which is not very cold, but maintains a temperature of about -0.5 to -1.0C at 10m depth.

The coordinates of the site are about 65 degrees 13 minutes North and 126 degrees 31 minutes West. Its elevation is 107 m ASL. A topographical map showing the location of the site is given in fig. 15. The Mackenzie River lies just to the southwest, and a mountain range to the north. Figure 16 shows the location of the thermocable (T4) relative to the pipeline. Figures 17 and 18 are air photographs of the location, while figs. 19 and 20 show the local terrain at ground level. In fig. 17 the site is marked by the arrow labelled A. The buried pipeline is easily visible as a straight white vertical line in the cleared strip which is the 'right of way'. Canyon Creek runs horizontally across the top half of the photo. Up the slopes, on either side of the creek along the right of way, the strip appears white. This is due to the fact that the slopes were covered with wood chips in an

attempt to thermally insulate them and to prevent erosion. Without this insulation there would be permafrost degradation on the slopes as the soil surface warmed as a result of the pipeline induced disturbance. Recent data indicates that the slope is warming more than it would have without the chips, however. Dr. Harry Baker (NRC) is monitoring the temperature profile in the wood chips in order to determine precisely their thermal impact on the underlying permafrost. Figure 18 shows a closer areal view taken in Nov. 1984. In fig. 19 the hut housing the datalogger can be seen towards the right of the bottom photo. In the centre where a wooden structure can be seen, lies the thermocable. Figure 21 is a climate graph similar to that in figure 15. It uses data taken from the observing site at Norman Wells airport. Note that it is colder than Schefferville, having a mean annual temperature of -6.2 C, but has much less precipitation, with an annual snowfall of only 141.5 cm and rainfall of 188.9 mm. The precipitation at the airport is not likely representative of that at the site, especially for snowfall, due to local effects. Certainly snow depth is greater at the site than at the airport.

The climate at Norman Wells is less severe with regard to wind and ice accretions than the one at Schefferville but has lower winter temperatures.

3.1.3 Churchill

The station at Churchill is located at thermocable RCT-1 some 400m east of the control tower at the Churchill airport. The thermocouple cable was installed in late September, 1973 under the superision of Dr. J.J.E. Brown of DBR/NRC. The cable is sited in solid Ordovician sandstone with no overburden other than shallow pockets of soil in cracks and depression on the bedrock surface. Little or no vegetation is present at the site, but large blocks of sandstone create a surface roughness which causes a rather uneven distribution of snow which varies with the amount of snowfall and the direction of the latest snow-driven wind. Previous temperature records indicate that the rock is of relatively high thermal conductivity. The depth of the active layer at the site exceeds 7.3m most years and the seasonal amplitude at the lowest sensor is some 3 C.

Figure 22a is a topographical map showing the local terrain around the site. Figure 22b is an air photograph of the area. Note the proximity of Hudson Bay just to the north, and of the airport just to the southwest. Figures 23 to 26 are photos showing the local terrain at ground level. The airport can be seen in the top photo of fig. 23. In the top photo of fig. 24 the thermocable site can be seen (in the right half of the photo). The ice covered bay is visible along the horizon. The bottom photo shows, nearby, a large rock formation. This increases local snow drifting, and also the risk of polar bear

encounters, as it provides them with an excellent hiding place. The hut housing the datalogger is shown in fig. 25. Figure 27 is another climate map similar to the ones presented for the previous stations. Churchill is colder than both Norman Wells and Schefferville, having a mean annual temperature of -7.2 C. It receives an average annual snowfall of about 191 cm and a rainfall of 233.4 mm. Winter snowfall is quite variable, ranging from about 35 cm in 1944 (an unusually low precipitation year) to around 360 cm in 1961. There seems to have been an increasing trend in snowfall since 1975, away from the relatively low values recorded since 1962. Since 1970 there have been large year to year variations in mean annual temperatures.

3.1.4 Mayo

Seven cables were installed near Mayo in July 1985. The sites are located about 3 km south of Mayo, at an elevation of about 605 metres ASL. Of the seven monitoring stations, five are located in fine-grained, glacio-lacustrine deposits, and two are in more recent, coarser alluvial material. Several actively expanding thermokarst lakes are found in the study area (Burn 1982), as well as two retrogressive thaw slumps (Burn et al 1986).

The dominant tree species is white spruce, with some paper birch, alder, balsam poplar and willow. The shrub layer consists of such species as wild rose, arctic lupine, wild rhubarb and twinflower. The ground is frequently covered by a layer of peat, moss or lichen. The microclimate at the thermocable sites is marginally represented by that of the climate station.

A complete description of the Mayo site is given in Smith and Burn (1986). Figure 28 shows the site location (box just south of Mayo) on the same scale as previous topographical maps, while fig. 29 shows the area on a larger scale. Another climate graph similar to the ones shown earler is presented in fig. 30. This location is relatively warm compared to the other sites, having a mean annual temperature of -3.7 C. However its climate is more variable, with the standard deviation of the mean annual temperatures being 1.5 C as opposed to 1.0 to 1.1 C for the other locations. Its precipitation is not large, winter snowfall being 121.8 cm and annual rainfall amounting to 184.7 mm on average.

Figures 31 and 32 are areal photographs of the region, while figures 33 and 34 show typical sites at ground level.

3.1.5 Station Data Summary

Station	Time Period of Observations	Comments
Mayo	Feb. 15,1986 to July 15,1986 Aug. 7,1986 to Mar. 12,1987	Monthly soil temps for 7 sites. Twice daily soil temps for site #7. Bad thermistor at 1.5m. Data collection ongoing.
Norman Wells	May 28,1986 to Oct. 16,1987	Soil moisture msg. or unreliable. Problem with 1m & 2m Oct. - Dec., 1986. Data collection ongoing.
Churchill	Dec. 3,1985 to March 23,1986 May 8,1986 to Jan. 24,1988	0.5m missing up to Feb. 11, 1986. Air temp & relative humidity missing June 8, 1986 to Aug. 7, 1987. Aug. 4-6, 1987 msg. Data collection ongoing.
Scheffer-ville	Apr. 19,1985 to Feb. 17,1988	Some data gaps, especially Aug. 19, 1986 to Oct. 19, 1986. Data collection ongoing.

3.2 Data Sampling and Instrumentation

The permafrost observing stations at Schefferville, Norman Wells, and Churchill are all equipped with Campbell Scientific 21X dataloggers, and AM32 32-channel multiplexers. At Mayo, a Campbell Scientific CR21 datalogger is being used at one of the sites and a CR10 at another. Cassette tape recorders were installed at all sites to store and retrieve data from the logger. The cassette recorders did not function well on cold days and they were replaced with Campbell Scientific SM64 solid state storage modules, a type of storage module already in place at Mayo.

Originally, all stations, with the exception of the one at Mayo, were powered by 32 alkaline D-cell batteries. Although this method worked satisfactorily, it was found to be very labour intensive and costly. A solar panel and rechargeable batteries were installed at Norman Wells in May 1987 and at Churchill and Schefferville in August 1987. The stations at Mayo are powered by six 12-volt lantern batteries.

At Norman Wells where a thermistor cable is used, the datalogger, AM32 32-channel multiplexer, storage module, and power supply are stored in a barrel which is buried in the ground. The barrel is

surrounded by a 3.6 x 3.6 metre insulated shelter which is designed to provide a stable thermal environment for the logger and also to minimize potential damage from vandalism. A similar configuration is used at Churchill and Schefferville where constantan thermocables are used, but the AM32 multiplexer is housed in an insulated enclosure at the cable head.

Heavy duty Met One wind direction and speed sensors, Sierra tipping bucket rain gauges, Campbell scientific model 207 or 207C air temperature and humidity probes, Gill multiplate radiation shields and model 227 Delmhorst cylindrical soil moisture blocks are used to monitor the meteorological conditions whenever the conditions at the A.E.S observing site are not representative of those at the permafrost site. Ten-metre towers were used to mount the wind sensors at both Schefferville and Norman Wells, but the one at Schefferville was replaced with a Campbell Scientific CM10 instrument tripod after the tower was stolen in August, 1986. No wind measurements are taken at the Churchill or Mayo permafrost sites, although they are of course observed at the local weather stations.

A listing of the configuration of the stations and the frequency of observations is presented below:

Element	Schefferville	Norman Wells	Churchill	Mayo
Air Temperature	hourly	hourly	hourly	nil
Relative Humidity	hourly	hourly	2-hourly	nil+
Wind	hourly	hourly	nil+	nil+
Soil Moisture	hourly	daily	nil+	nil+
Snow Depth	hourly	hourly(Sep.-May)	hourly	*monthly
Rainfall	hourly	daily	nil+	nil+

* Manual readings are taken twice monthly from June 1 to October 31 and monthly at all other times.

+ Observations of these parameters are taken at nearby AES climate stations.

The thermocables at Schefferville and Churchill are copper-constantan thermocouples while those at Norman Wells and Mayo employ thermistors. The depth of the ground sensors and the frequency of observations are given in the following table.

Schefferville	**Norman Wells	Churchill	*Mayo
Depth/freq.			
1.5m/hourly	1m/hourly	0.5m/hourly	0.5m/monthly
2.3m/hourly	2m/hourly	1.2m/2-hourly	1.0m/monthly
3.1m/hourly	3m/daily	2.0m/2-hourly	1.5m/monthly
3.8m/hourly	4m/daily	2.7m/2-hourly	2.0m/monthly
4.6m/daily	5m/daily	3.5m/6-hourly	3.0m/monthly
5.5m/daily	6m/daily	4.3m/6-hourly	4.0m/monthly
6.2m/daily	7m/daily	5.8m/6-hourly	5.0m/monthly
7.5m/daily	8m/daily	7.3m/6-hourly	
9.2m/daily	9m/daily	8.8m/daily	
12.2m/daily	11m/daily	10.4m/daily	
15.2m/daily	13m/daily	11.9m/daily	
		14.9m/daily	

* At Mayo, cables 1 to 5 are read manually twice monthly from June 1 to October 31 and monthly at all other times. Cables 6 and 7 are read twice per day by the CR21.

** A new cable was installed at Norman Wells during the summer of 1987. Observations are now taken at 0.5m in addition to the ones at greater depths, with the exception of 8m which was discontinued.

3.3 Problems

There are several sources of problems in setting up untended data gathering stations, ranging from mechanical, to climatic, to human.

Initially all data were recorded on tapes. Unfortunately the tape recording speed has at times during the winter been affected by cold temperatures. This has been most prevalent at Churchill, where the datalogger and tape system are less protected from cold temperatures, only a slight problem at Schefferville and no problem at Norman Wells. The effect of the change in tape speed is unreadable data. This has been corrected by using solid state memory devices which are much less susceptible to cold temperatures.

At first, the proximity of the hut housing the datalogger to other equipment such as those recording temperature and humidity resulted in some data contamination. This was corrected by moving the sensors farther from the hut and painting the hut white at Norman Wells and Schefferville so that it would not heat up as much due to solar radiation. At Churchill the hut was left black as that colour better matched the local terrain (dark rock).

Initially the Norman Wells site showed some strange periodicities in the data. A rewiring of the system corrected it, although the cause is still unknown. Several thermistors appear to be giving, intermittently, incorrect readings, especially at 11m, 7m and 4m. Other data problems appear to be the result of moisture getting into the connections during periods of manual readings. A second cable, permanently connected to the logger, was installed in the summer of 1987 in order to correct this problem.

The Schefferville site was, unfortunately, vandalized Aug. 19, 1986. This resulted in some loss of data. The stolen equipment was replaced the following October. The cable there shorts out between 6.2 and 7.5 m; as well between Nov. and Dec. of each year there is a short between 1.5 and 2.3 m.

The ground temperature data at Churchill shows large (about 0.5C) high frequency fluctuations of unknown cause. As well, random shorts occur between 7.3 m and 8.8 m .

Thermopile ladder snow depth sensors were installed at Schefferville, Norman Wells,and Churchill, but they did not prove satisfactory and have been replaced by ultrasonic snow depth sensors (Goodison et al, 1984).

4 Analysis

4.1 Overview

This project will generate a very large dataset. In order to facilitate analysis of the large amount of data collected at the various sites, and to provide quick but descriptive qualitative analyses, it was decided to archive the data on the mainframe system at AES and to have a specialized computer program which would show such properties as variation or trend, or correlation through visual comparison. Beyond this statistical approach, it is fundamental to look at the thermal properties of the system from a physical point of view.

4.2 The Software

A user-friendly software package was developed to store and display the data. When received the data is stored on magnetic tape in the tape library in the Downsview Computer Centre. Programs exist which will process, edit, print out or graph the data.

Tables 2 and 3 are examples of printouts from Norman Wells. The first table illustrates data collected on a daily basis. The second table shows data collected more frequently. The printouts for the other stations are similar.

4.3 Graphs

The software package plots time series graphs, depth graphs, and annual envelope profiles. These three types of graphs are illustrated in figs. 35 to 39, for Norman Wells, Churchill and Schefferville.

4.4 Quasi-Thermal Diffusivities

Temperature graphs (depth and time-series) and the calculation of 'diffusivities' from the general heat conduction equation allow for a characterization of the ground thermal regime at each site. The calculated 'diffusivities' are not precisely thermal diffusivities, but are augmented by heat transfer processes other than conduction. It is therefore possible to identify certain non-conductive heat transfers by considering the magnitude of the calculated 'diffusivity'. Details of this technique are given in Stoker (1987).

The Churchill site has the most straightforward ground thermal regime of the monitoring sites. Conduction is virtually the only mechanism of heat redistribution, as the subsurface is massive sandstone. It is therefore possible to follow surface temperature changes into the ground with the expected damping and time-lag effects (fig. 35). As a result ground temperatures exhibit great variation throughout the year as shown by the annual temperature envelope (fig. 39). Since the Churchill data is affected by minor instrument noise, use of the general heat conduction equation yielded poor results. The technique worked well for the other sites.

It was found that the soil thermal regimes at Mayo are heavily influenced by moisture. Even near-surface temperatures are remarkably constant and remain near 0C, while evidence for strengthened conduction exists when the soil dries. The

calculated 'diffusivities' indicate that freeze-thaw and perhaps evaporation/condensation are most important in heat transfers. Deeper soil temperatures tend to be affected by a greater mobility of water.

Mass-heat flows (water) are important to the ground thermal regime at Schefferville; less so from 4m to 6m where the conduction component is strong (this is possibly due to a lower moisture or ice content). Near the surface rapid temperature changes can occur (fig. 36) and cryogenic suction is probably important. Cold temperatures penetrate deeply as most of the snow is carried away by wind.

At Norman Wells conduction prevails above 4m and below 11m, where the subsurface is consolidated (although above 4m latent heat effects are significant). Between 4m and 11m freeze-thaw latent energy exchanges dominate the thermal regime and clear seasonal patterns in the calculated values can be identified. Fig. 38 illustrates the 1m soil temperature response to changes in air temperature.

The thermal regimes at Mayo and Schefferville are influenced by moving water, while latent heat effects at Norman Wells hold temperatures near freezing. Figure II shows the annual temperature envelopes for Schefferville, Churchill and Norman Wells.

A fuller analysis will be presented in a future report.

4.5 Numerical Heat Flow Model

An in-house model is in the process of being developed, suitable for being driven by boundary conditions supplied by climate scenario models. Other numerical models of permafrost have been developed by researchers such as M. Smith (Smith, 1975), S. Outcalt (Outcalt and Brown, 1977) and L. Goodrich (Goodrich, 1982). Smith's model, as yet, is not available, however the Goodrich model was obtained in Sept., 1986. Eventually these two models will be run on identical cases for comparison purposes.

The numerical integration scheme used by the in-house model is taken from Albert, (1983) At any point in the grid thermal and material properties can be specified. It allows for phase change as specified by the user. Upper boundary conditions are specified with a constant temperature (the air temperature). No horizontal heat flow is allowed. Bottom boundary conditions are specified either by a constant temperature, or by a constant upward geothermal heat flux. The heat flow can be solved with variable mean monthly snow depths. If air temperatures rise above 0C, then melting or sublimation occurs. Various simplifying assumptions are made in order to make the snow portion of the heat flow problem tractable.

Figure 40 illustrates changes in temperatures within a hypothetical soil (from the in-house model) resulting from a linearly increasing air temperature over a 20 year period. The

effect of snow is not included. Note how 0 C acts as a 'barrier'; the energy absorbed in the phase change inhibits further temperature rise. The results of Smith and Riseborough (1983) indicate that linearly increasing soil surface temperatures in response to a climate warming (fig. 43) is a reasonable assumption. A full description of this model will be the focus of a separate report.

5 Discussion and Recommendations

It is difficult to underestimate the importance of climate to permafrost, although there is no doubt that it responds to many non-climatic parameters. The problems involved in modelling permafrost and permafrost related processes are challenging indeed, and a considerable amount of progress is needed. Smith (1986) noted that "...we know very little in a definite way about the specific relationship of climate to permafrost processes and the ground thermal regime. Further, in terms of significance to us, the key question is how quickly will permafrost conditions change? This is not simply a matter of how quickly changes in climate per se will develop, but is compounded by the question of how the effects of climate on permafrost conditions will be modulated by the environment."

A long-term data collection program is important in acquiring the data required in order to develop an increased understanding of the relationships involved. This program is a first step in such a process.

Recommendations:

1. That the data collection program continue to be supported over a 10 year period in order to collect a long-term data base.

2. That funding be made available for mesoscale impact studies in areas of particular significance, such as along the Mackenzie Valley pipeline corridor.

3. It was noted during this project, that no data bank of permafrost related data existed, similar to the climate data archived at AES. It is recommended that some appropriate body (such as the NRC subcommittee or GSC) work towards a comprehensive and centralized permafrost archive, or at least towards a catalogue of permafrost data.

4. It is recommended that permafrost-climate research be done inter-departmentally (AES and EMR for example), as inter-disciplinary expertise is required.

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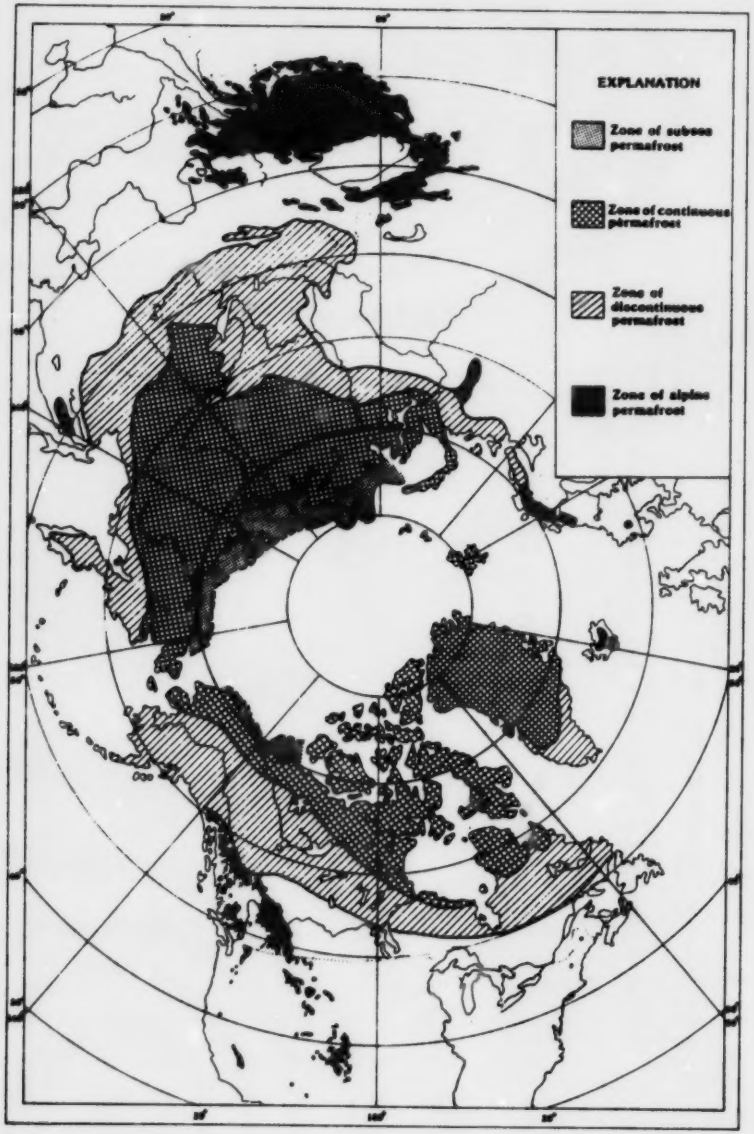
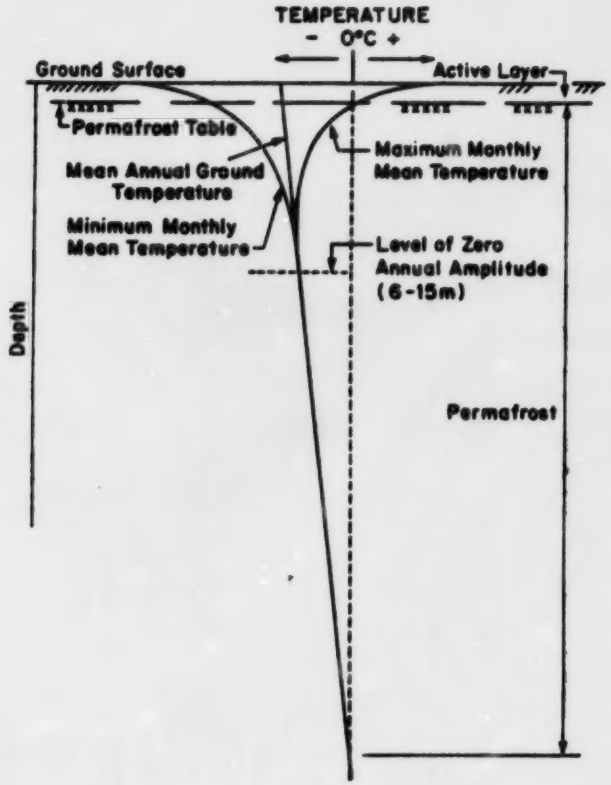


Distribution of permafrost in the Northern Hemisphere (compiled by T. L. Péwé 1983).

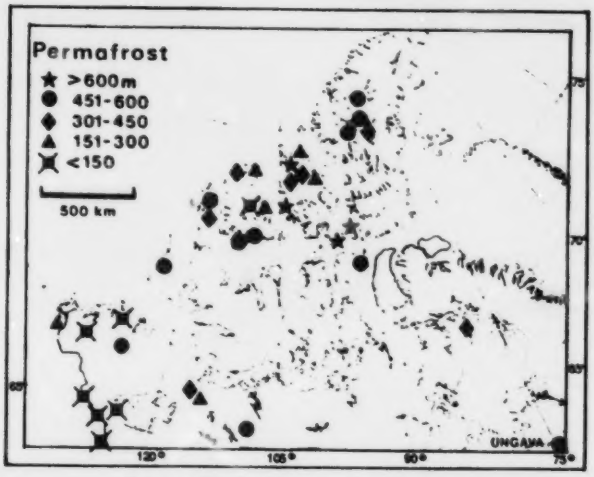
Figure 1



GROUND THERMAL REGIME IN PERMAFROST

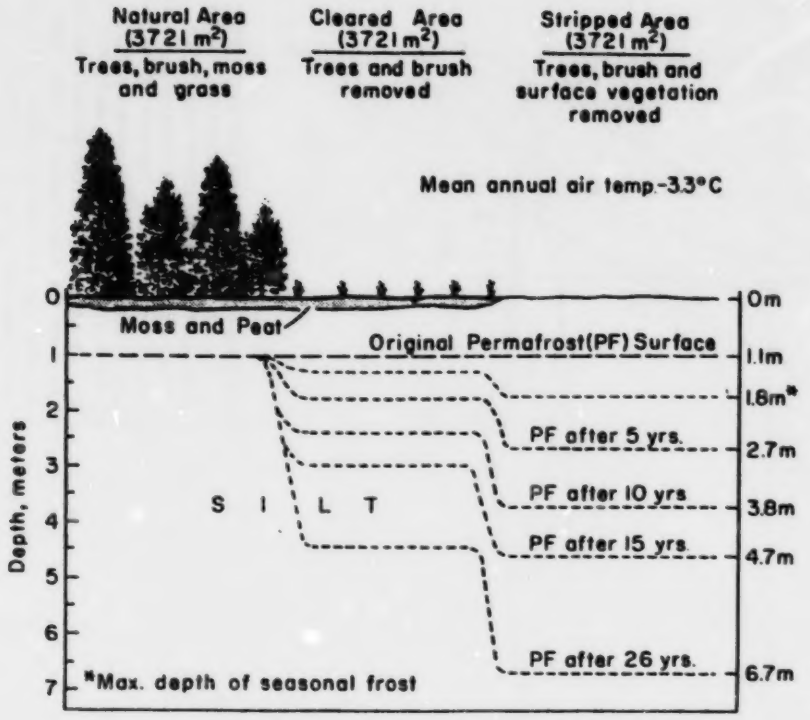
(Judge, 1973)

Figure 2a



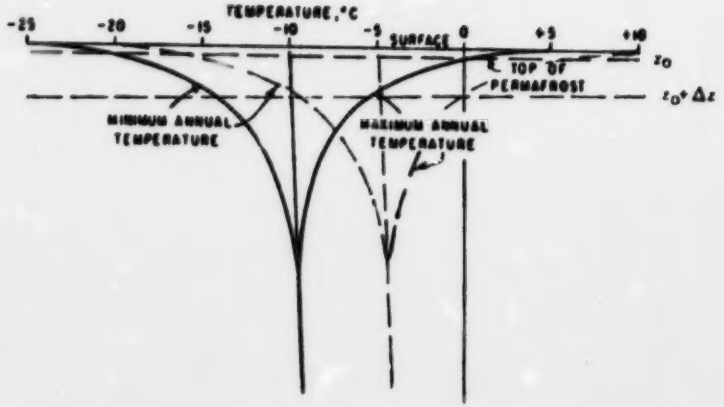
Permafrost thicknesses in northern Canada. Some symbols represent several determinations, and not shown are 40 sites in the Mackenzie Delta. Data from the Ungava region of Québec is represented by the symbol in the lower right corner.

Figure 2b



Change in permafrost table following clearing and stripping in the Fairbanks area (Linell, 1973).

Figure 3

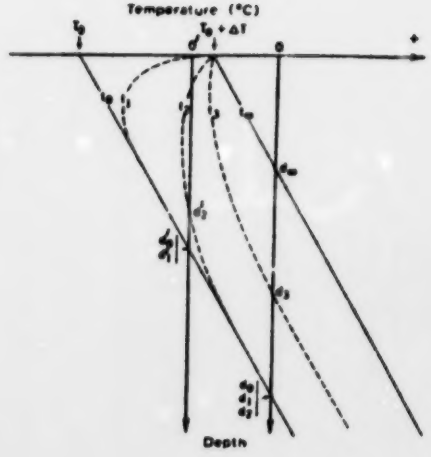


b) changes in surface temperature envelope and active layer (z_o to $z_o + \Delta z$) following increase in surface temperature, from -10^0 to -5^0C

ACTIVE LAYER RESPONSE TO CHANGES IN SURFACE TEMPERATURE

(Modified after Lachenbruch, 1968)

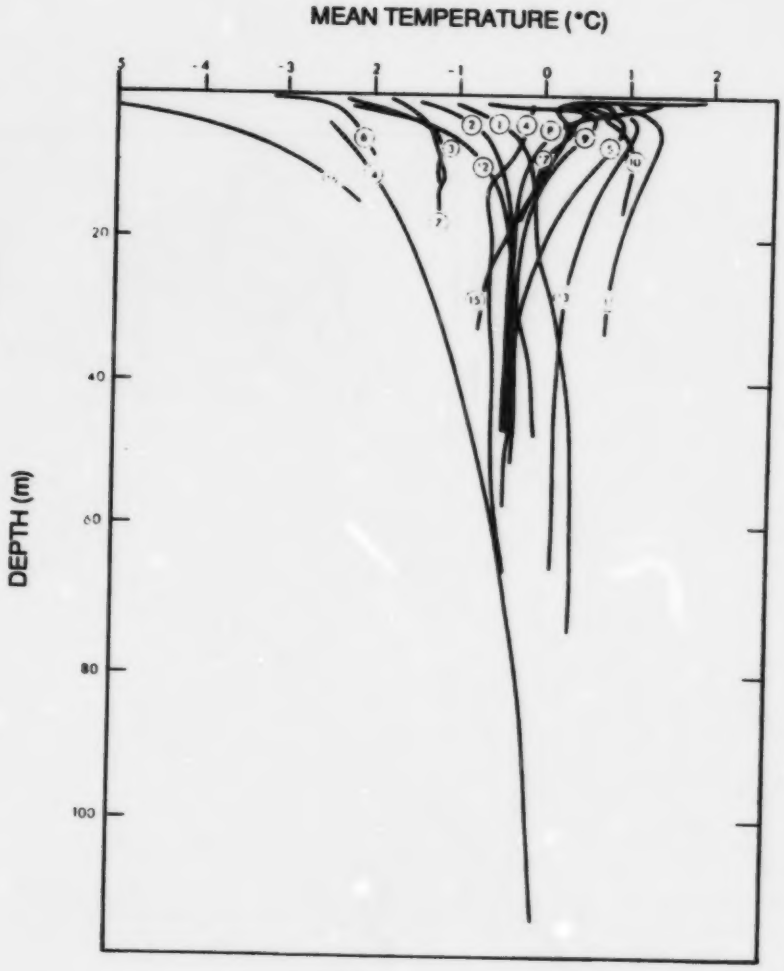
Figure 4a



Ground temperature at successive times (t_o, $t_1 \ldots t_\infty$) after an increase in mean ground surface temperature from T_o to $T_o + \Delta T$. If the final temperature is below 0°C (0°C lies at point 0), the base of permafrost rises successively from d_o to d_∞. If the final temperature is above 0°C (i.e. 0°C lies at point 0') the permafrost degrades first from the top (curve t_1) and then from both top and bottom (curve t_2), and finally vanishes (curves t_3 and T_∞) (Lachenbruch 1968).

PERMAFROST RESPONSES TO CHANGES IN SURFACE TEMPERATURE

Figure 4b



Mean temperatures against depth for 17 temperature profiles, showing the range of temperature conditions at the site.

Figure 5

Monitoring Site Locations

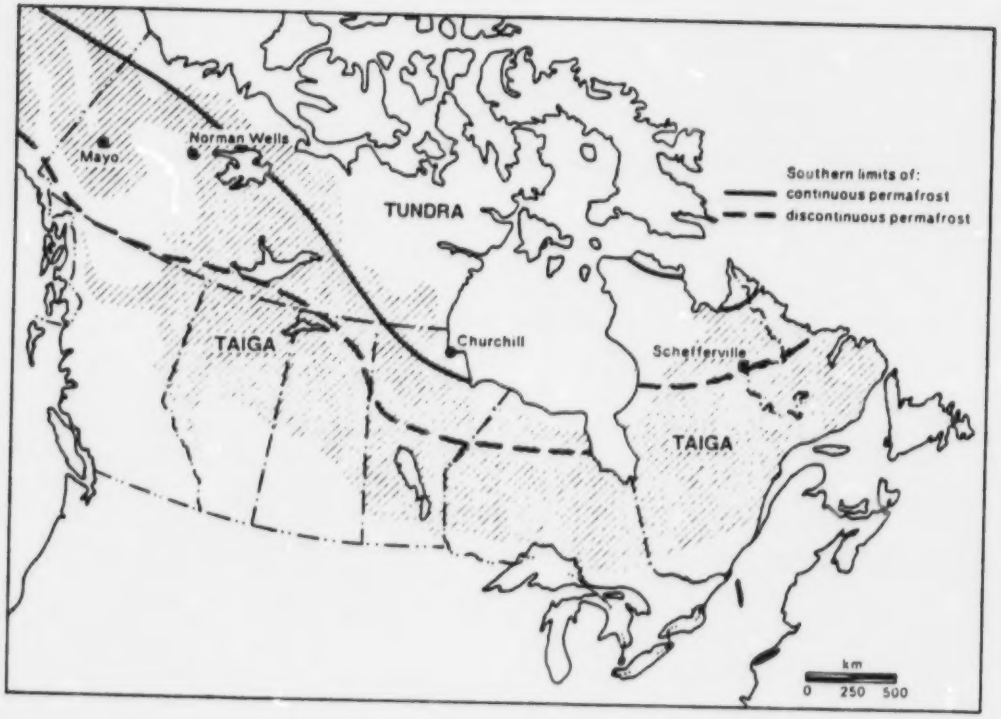
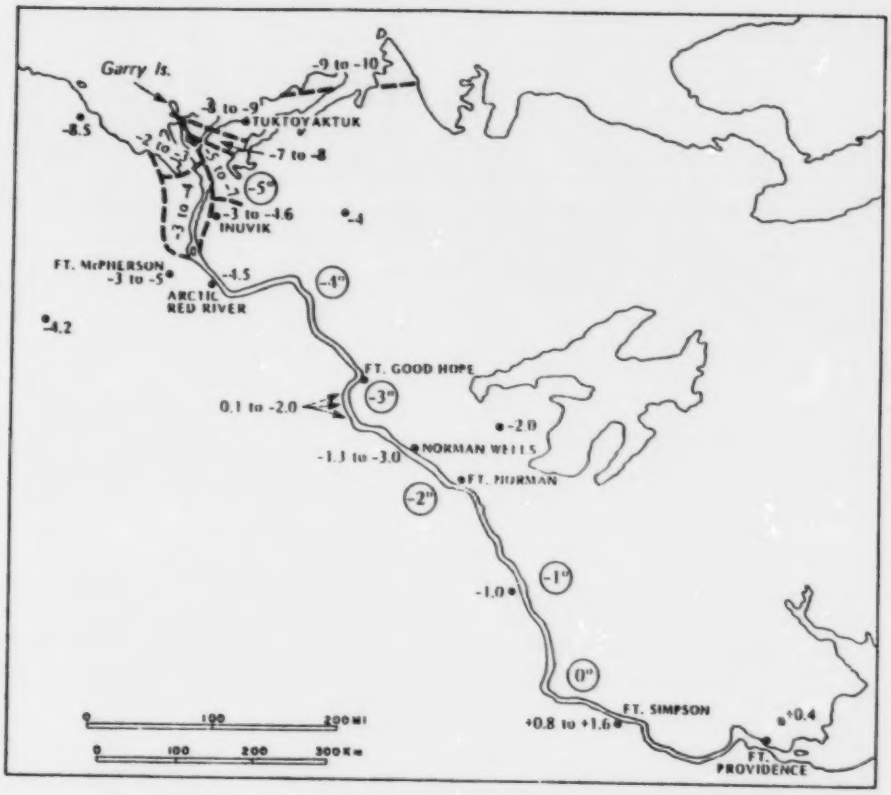


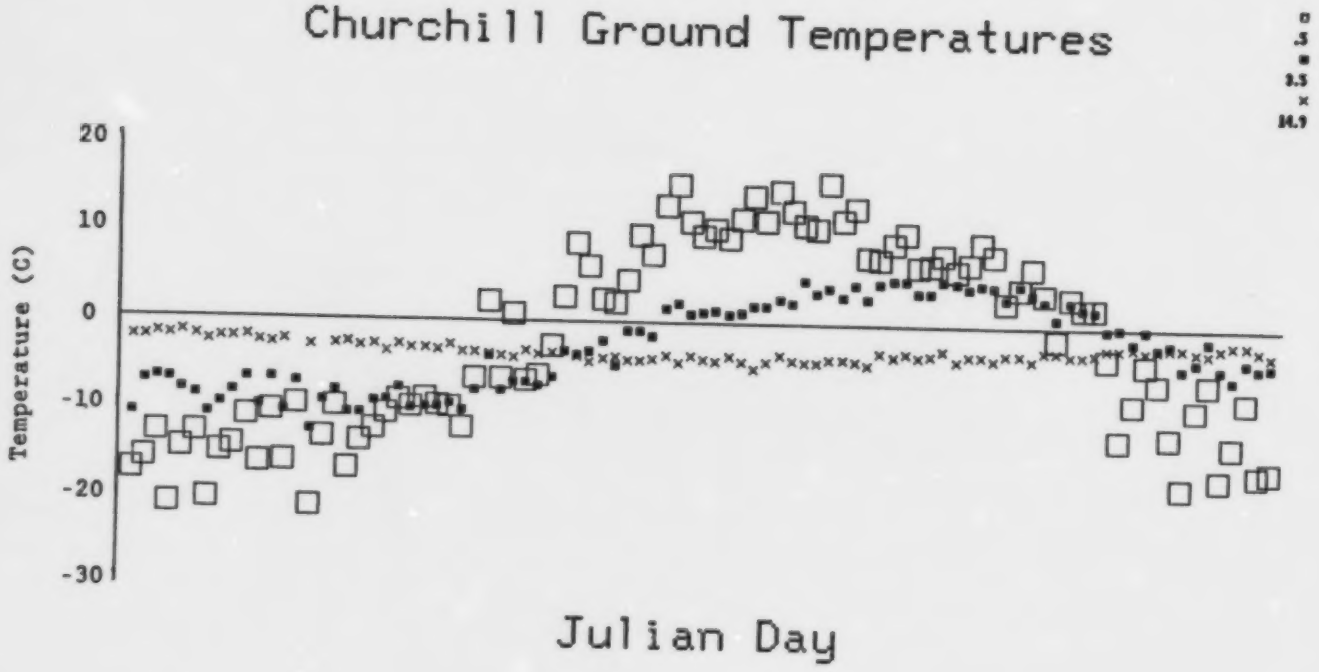
Figure 6



The circled numbers indicate the approximate mean annual ground temperatures in ^{o}C. At any given area, a temperature range of $\pm$ 1.5^{o}C is quite possible.

Mean annual ground temperatures (Mackenzie Valley)

Figure 7a



A scatter plot of all ground temperatures recorded at 0.5m, 3.5m and 14.9m from 1973 to 1983. The horizontal axis (Julian Day) is compressed to eliminate days with no observations. Thus the annual cycle appears distorted.

Figure 7b

Ground Temperature Data (Churchill), Cable RCT-1

Year	Day	.5	1.2	2	2.7	3.5	4.3	5.8	7.3	8.8	10.4	11.9	14.9
73	269	6.8	5.8	5.1	4.4	3.8	3.3	1.8	.4	-1.1	-2	-2.7	-3.7
73	348	-6.3	-4.1	-2.7	-2	-1.3	-1.2	-.9	-.9	-1.3	-1.7	-2	-2.8
74	72	-10.4	-9.4	-8.3	-7.5	-6.6	-6	-4.8	-3.9	-3.3	-2.9	-2.7	-2.7
74	154	2.7	.8	-1.1	-2.3	-3.3	-3.9	-4.4	-4.6	-4.4	-4.1	-3.8	-3.3
74	191	11.4	7.6	4.6	2.6	1.1	-.2	-1.9	-3	-3.5	-3.7	-3.8	-3.7
74	283	15	10.8	7.3	4.9	2.8	1.4	-.8	-2.2	-2.9	-3.4	-3.5	-3.6
74	246	7.6	7.3	6.7	5.8	4.8	3.7	1.7	-.1	-1.1	-1.9	-2.5	-3.2
74	345	-9.2	-7.3	-5.9	-4.7	-3.8	-3.1	-2.2	-1.8	-1.7	-1.9	-2.2	-2.6
75	186	-9.8	-10.2	-10.4	-10.4	-10	-9.3	-8	-6.8	-5.7	-4.7	-3.9	-3.1
75	170	4.8	3.2	1.5	.7	-1	-2.1	-3.7	-4.6	-4.9	-4.9	-4.8	-4.3
75	252	10.5	8.9	7.8	6.4	5.2	4.1	1.9	.3	-.9	-1.8	-2.3	-3.1
75	342	-10.1	-13.3	-9.4	-6.6	-4.6	-3.1	-1.4	-.8	-.8	-1.2	-1.4	-2.1
76	75	-21.3	-10.1	-15.7	-14.1	-12.6	-11.3	-9.1	-7.2	-5.8	-4.6	-3.8	-2.9
76	190	15.6	12.1	8	4.7	2.2	0	-2.2	-3.6	-4.3	-4.8	-4.6	-4.6
76	268	9.5	7.1	6.2	5.4	4.7	3.8	1.9	.3	-.8	-1.8	-2.5	-3.4
76	348	-17.2	-12.4	-8.9	-6.5	-4.6	-3.3	-1.7	-1.1	-1.1	-1.3	-1.6	-2.2
77	76	-9.9	-9.4	-9	-8.5	-8	-7.5	-6.4	-5.2	-4.4	-3.7	-3.3	-2.7
77	176	13.2	8.8	5.9	3.4	1.7	.2	-1.7	-2.9	-3.5	-3.8	-3.8	-3.7
77	258	8.2	8	7.1	6.1	5.2	4.3	2.5	1	-.1	-1.1	-1.7	-2.7
78	23	-14.7	-12.9	-11.8	-10	-8.1	-6.7	-4.3	-3.1	-2.2	-1.7	-1.6	-1.6
78	69	-16.4	-13.7	-12	-10.8	-9.9	-8.7	-7	-5.7	-4.6	-3.8	-3.2	-2.6
78	109	-9.8	-9.9	-10.3	-9.9	-9.5	-8.9	-7.6	-6.4	-5.2	-4.4	-3.7	-2.8
78	144	-2.8	-4.1	-5.3	-6	-6.3	-6.7	-6.5	-6.2	-5.7	-4.9	-4.3	-3.5
78	165	8.9	1.7	-1.1	-2.6	-3.8	-4.3	-5.1	-5.3	-5.2	-5	-4.6	-3.9
78	195	9.9	8.1	5.4	2.8	1.3	-.1	-2.1	-3.4	-4.1	-4.4	-4.4	-4.1
78	285	12.8	9	6.2	4.1	2.4	1.4	-1.5	-2.9	-3.7	-4.1	-4.2	-4.2
78	233	7.8	6.6	5.3	4.5	3	2.1	0	-1.7	-2.9	-3.4		-4.6
78	261	2.8	4	4.1	3.7	3.2	2.5	1.2	0	-.9	-1.7	-2.3	-3.1
78	273	3.8	3.6	3.5	3.3	3	2.6	1.4	.3	-.7	-1.5	-2.1	-2.8
78	324	-12.4	-8.7	-5.6	-3.4	-1.8	-1.2	-.3	-.4	-.7	-1.2	-1.6	-2.1
78	348	-13.4	-11.1	-8.6	-6.7	-5.7	-3.6	-1.9	-1.4	-1.2	-1.2	-1.3	-1.8
79	18	-12.9	-10.9	-9.2	-7.7	-6.7	-5.7	-4.2	-3.1	-2.3	-2	-1.7	-1.7
79	48	-14.4	-12.5	-10.6	-9.4	-8.2	-7.1	-5.4	-4.2	-3.6	-2.8	-2.5	-2.2
79	75	-13.4	-12.2	-11.1	-10	-9.3	-8.3	-6.8	-5.4	-4.4			
79	87	-12.3	-11.6	-10.8	-10.1	-9.3	-8.5	-7.1	-5.9	-4.8	-4.1	-3.4	-2.8
79	108	-9.7	-10.4	-10.5	-10.3	-9.8	-9.2	-7.9	-6.7	-5.7	-4.9	-4.1	-3.3
79	134	-6.4	-7.1	-7.6	-7.8	-7.8	-7.5	-7	-7.2		-5.1	-4.5	-3.5
79	148	-6	-6.7	-7	-7.2	-7.3	-7.3	-7	-6.6	-5.9	-5.3	-4.8	-3.7
79	173	7.7	4.9	2.3	.2	-1.6	-2.9	-4.5	-5.2	-5.4	-5.2	-4.9	-4.2
79	199	11.7	8.5	5.9	4	2.1	.4	-1.6	-3.2	-4.1	-4.4	-4.5	-4.3
79	227	10.8	8.4	7.2	6.7	3.6	2.1	-.1	-1.3	-2.3	-3		-4.4
79	256	6.8	6.1	5.4	4.7	3.8	3.1	1.3	-.2	-1.4	-2.2	-2.9	-3.6
79	257	6.9	6.2	5.3	4.5	3.7	2.8	1.2	-.3	-1.4	-2.2	-2.8	-3.3
79	288	-1.3	-.3	.4	.7	1	1	.6	0	-.8	-1.4	-2.1	-2.8
79	323	-6.2	-5.6	-4.3	-3.1	-2.1	-1.2	-.7	-.7	-.9	-1.4	-1.8	-2.4
79	350	-16.6	-11.9	-8.6	-6.2	-4.4	-3.4	-2	-1.6	-1.4	-1.6	-1.8	-2.3
80	15	-16	-13.4	-10.7	-8.7	-7	-5.7	-4.1	-3.1	-2.4	-2.2	-2.1	-2.2
80	46	-12.9	-11.3	-10.3	-9.5	-8.6	-7.7	-5.7	-4.3	-3.6	-2.6	-2.4	-2
80	76	-16.9	-15.3	-13.4	-11.9	-10.6	-9.3	-7.3	-5.9		-3.7	-3.1	-2.5
80	85	-13.8	-13.3	-12.6	-11.7	-10.7	-9.7	-7.8	-6.2	-5.1	-4.3	-3.7	-2.9
80	107	-8.9	-9.7	-10.2	-10.2	-9.8	-9.3	-8.1	-6.9	-5.7	-4.8	-4.1	-3.2
80	136	2.3	.2	-1.7	-3.1	-4	-5	-5.8	-6.1	-5.8	-5.2	-4.8	-3.7
80	171	9.9	5.2	2.3	.4	-1	-2.1	-3.5	-4.3	-4.7	-4.8	-4.8	-4.4

Table 1

Ground Temperature Data (Churchill), Cable RCT-1

Year	Day	.5	1.2	2	2.7	3.5	4.3	5.8	7.3	8.8	10.4	11.9	14.9
80	197	11.9	9	4.9	2.9	1.2	0	-1.6	-3	-3.7	-4.1	-4.3	-4.3
80	228	11.8	8.9	6.5	4.9	3.1	2.1	0	-1.2	-2.4	-3.3	-3.5	-3.9
80	251	9.3	8.2	7.2	6.2	5.1	3.8	1.8	0	-1.4	-2.2	-2.9	-3.6
80	261	4.4	6.1	6.1	5.4	4.7	3.7	1.8	.2	-.9	-1.9	-2.6	-3.2
80	320	-8.7	-5.6	-3.7	-2.4	-1.6	-.8	0	-.2	-.7	-1.1	-1.5	-2.2
81	14	-17.3	-16.5	-14.8	-12.9	-10.9	-9.1	-6.1	-3.9	-2.9	-2.2	-2.1	-2.1
81	46	-20.5	-17.9	-15.1	-12.8	-10.9	-9.4	-7.3	-5.8	-4.5	-3.6	-3.1	-2.6
81	105	-10.6	-10.2	-9.6	-9.3	-9.1	-8.5	-7.5	-6.5	-5.6	-5	-4.4	-3.6
81	136	-6.4	-7	-7.7	-8.1	-7.9	-7.8	-7.6	-6.7	-6	-5.3	-4.8	-3.9
81	166	6.4	2.4	-.3	-2.1	-3.4	-4.3	-5.4	-5.9	-5.9	-5.7	-5.3	-4.6
81	197	14.4	8.8	6.8	4.3	2	.5	-2.2	-3.7	-4.6	-5	-5.2	-5
81	226	11.2	10.7	8.6	6.7	4.9	3.2	.5	-1.6	-2.8	-3.6	-4	-4.4
81	258	6.3	6.4	6.3	5.8	4.9	3.9	2	.3	-1.3	-2.4	-2.8	-3.9
81	288	3.4	3.8	3.7	3.4	2.9	2.5	1.5	.4	-.5	-1.3	-2.1	-3.1
81	318	-3.6	-3.1	-2	-.9	-.1	0	.2	.1	-.5	-1	-1.6	-2.4
82	18	-21.1	-15.8	-11.9	-9.1	-6.8	-5.3	-3.3	-2.1	-1.6	-1.3	-1.8	-1.9
82	46	-15.2	-13.7	-12.4	-11	-9.6	-8.3	-6.2	-4.1	-3.1	-2.5	-2.1	-2.1
82	74	-16.2	-14.6	-12.9	-11.3	-10.5	-9.3	-7.4	-5.9	-4.4	-3.4	-2.9	-2.4
82	109	-12.2	-13.3	-11.8	-11.2	-10.2	-9.7	-8.2	-7.2	-6.4	-5	-4.3	-3.5
82	137	.8	-2.3	-4.1	-5.1	-6.9	-8.3	-7.9	-8.1	-7	-6	-5.2	-4.1
82	166	2.6	1.3	.3	-1.1	-2.2	-3	-4.3	-4.9	-5.1	-5.1	-4.8	-4.1
82	196	10.6	8.1	5.3	2.9	1.4	.2	-2	-3.3	-3.7	-4.3	-4.4	-4.3
82	228	13.3	11.3	8.6	6.9	4.5	3	.4	-1.3	-2.4	-3.4	-3.7	-4.2
82	258	7.1	6.9	6.6	5.4	4.4	3.4	1.6	0	-1.2	-2.2	-2.9	-3.4
82	288	2.3	2.9	2.9	2.8	2.2	2.2	1.4	.6	-.7	-1.5	-2.1	-3.2
82	319	-12.7	-6.6	-3	-1.1	0	0	0	0	-.4	-1.1	-1.4	-2.3
82	348	-8.2	-6.6	-5.1	-4.3	-3.8	-2.9	-1.7	-.6	-1.2	-1.1	-1.2	-1.7
83	58	-11	-9.6	-8.5	-7.6	-6.6	-5.9	-4.6	-3.4		-2.5	-2.2	-1.9
83	74	-9.7	-8.8	-8.7	-7.4	-7.1	-6.7	-5.4		-3.8	-3	-2.8	
83	105	-9	-8.4	-8.1	-7.6	-7.6	-6.9	-6.1	-5.1	-4.4	-3.7	-3.4	-2.7
83	139	-6.7	-6.9	-7	-7.1	-6.9	-6.7	-6.2	-5.7	-5.2	-4.4	-4	-3.3
83	166	2.3	-1.4	-3.1	-4.2	-4.8	-5.3	-5.7	-5.7	-5.5	-5	-4.6	-4
83	196	9.7	8.6	6	3.5	1.1	-.2	-2.6	-3.8	-4.3	-4.3	-4.3	-3.8
83	227	16.1	11.7	8.9	8.6	4.2	2.1	0	-1.6	-2.6	-3.2	-3.7	-3.9
83	260	8.2	7.2	6.4	5.6	4.6	3.6	2	0	-.8	-2.2	-3.1	-3.7
83	288	2.2	2.6	2.4	2.3	2.1	1.7	.6	0	-.7	-1.4	-2	-2.9
83	322	-4.1	-3.1	-1.9	-.8	-.1	0	0	-.4	-.6	-1	-1.7	-2.5
83	350	-16.2	-11.2	-8.2	-6.8	-4.1	-2.9	-2.1	-1.1	-.6	-.7	-1.4	-2.9

Table 1

SCHEFFERVILLE

Schefferville: topographical map

scale 1:250,000

Figure 8a

Schefferville: air photo

Figure 8b

Schefferville: ground site photos

Figure 9

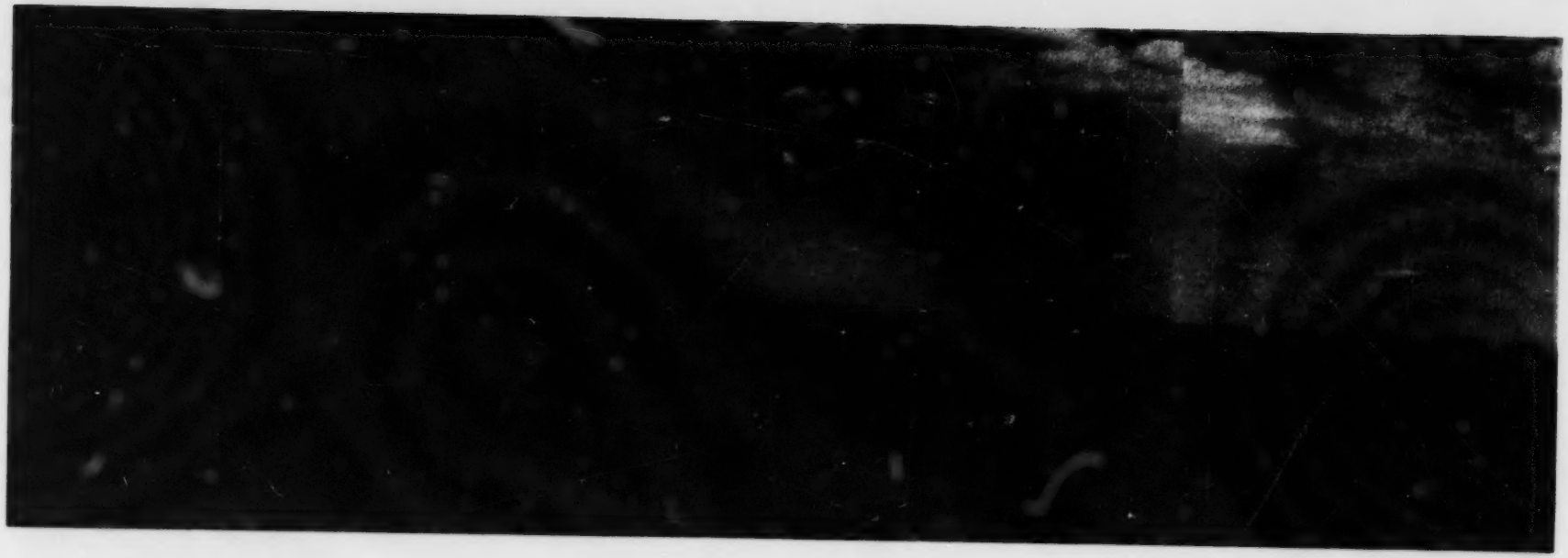


Figure 10

Figure 11

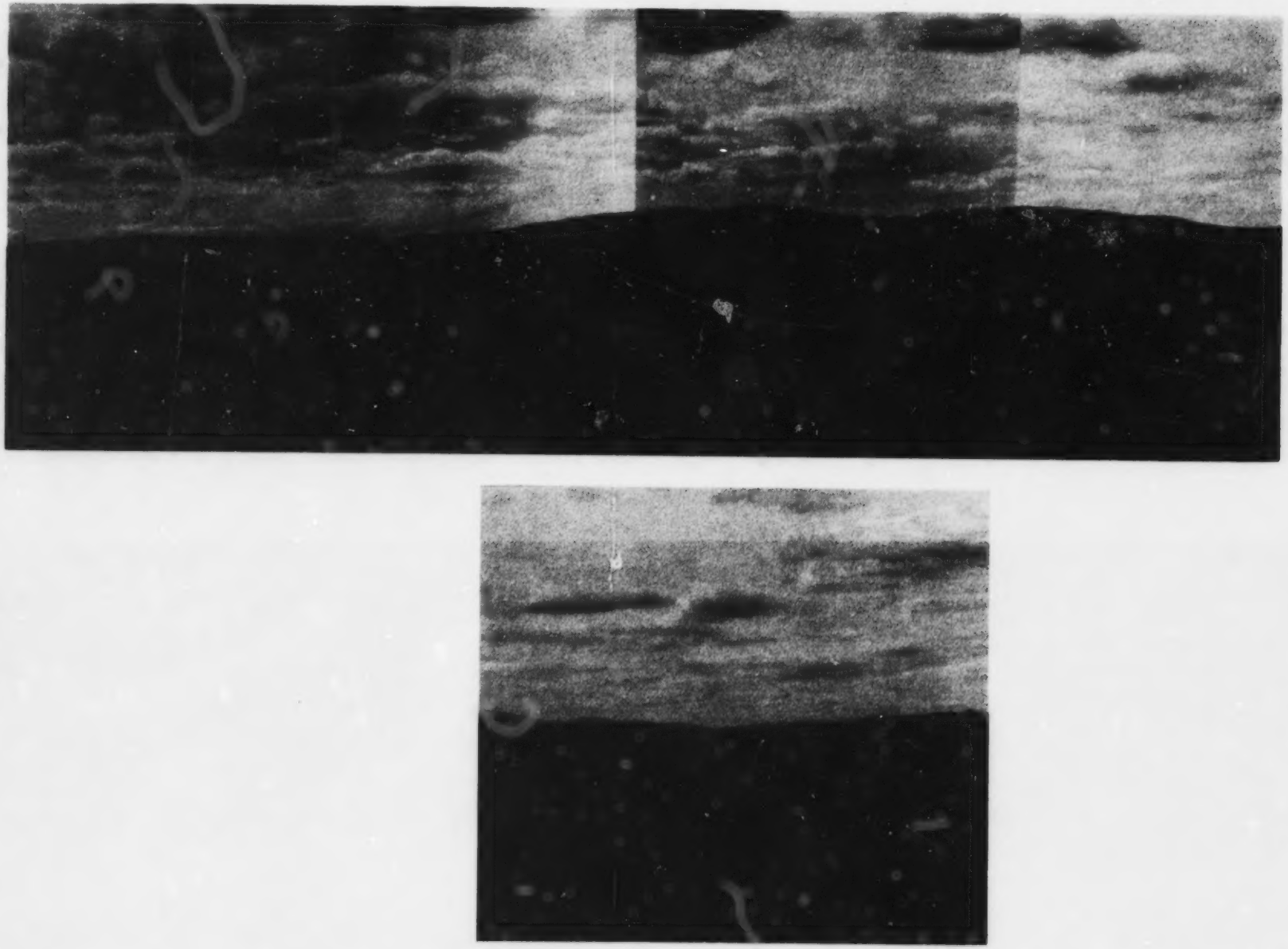
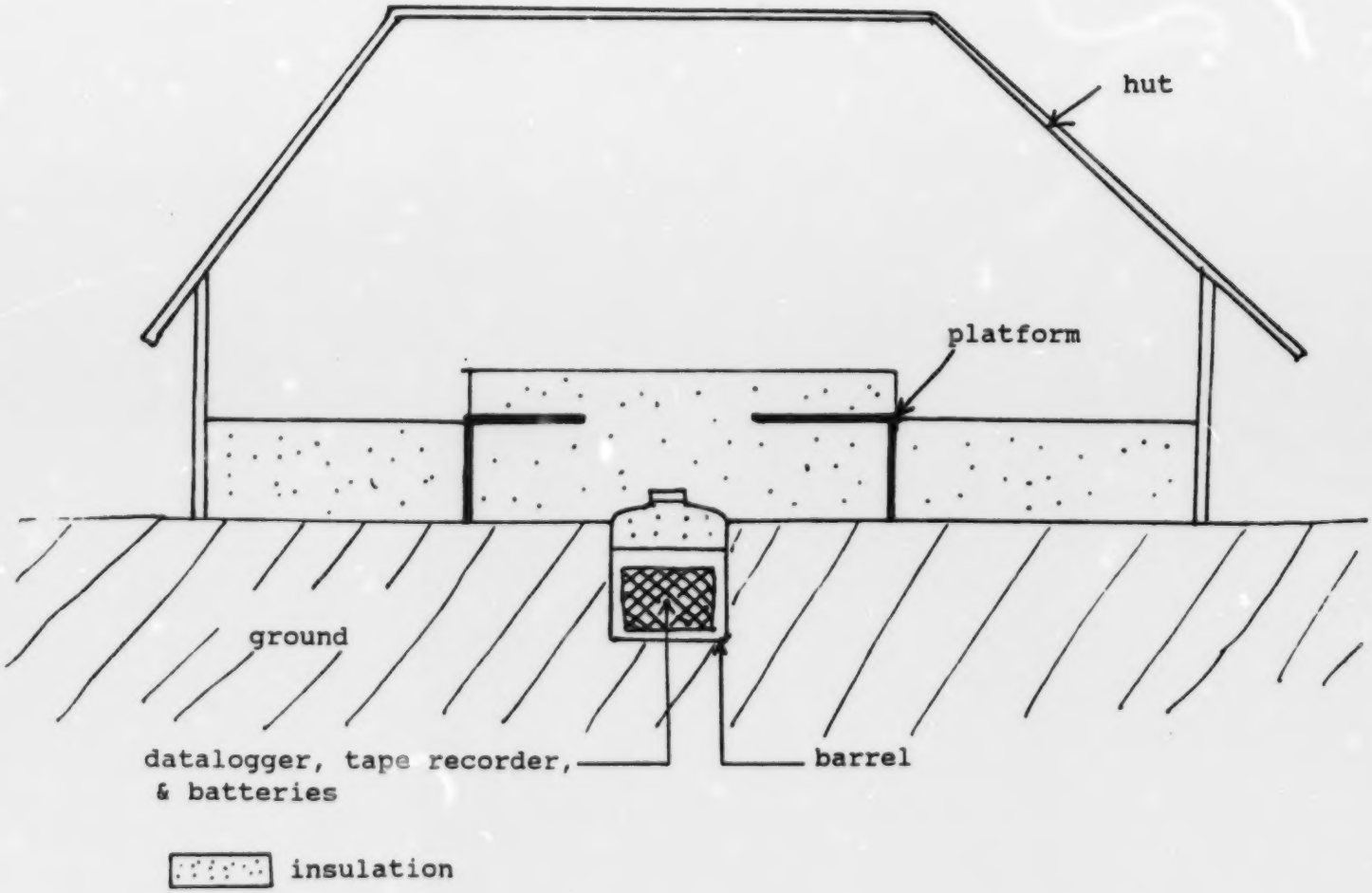


Figure 12

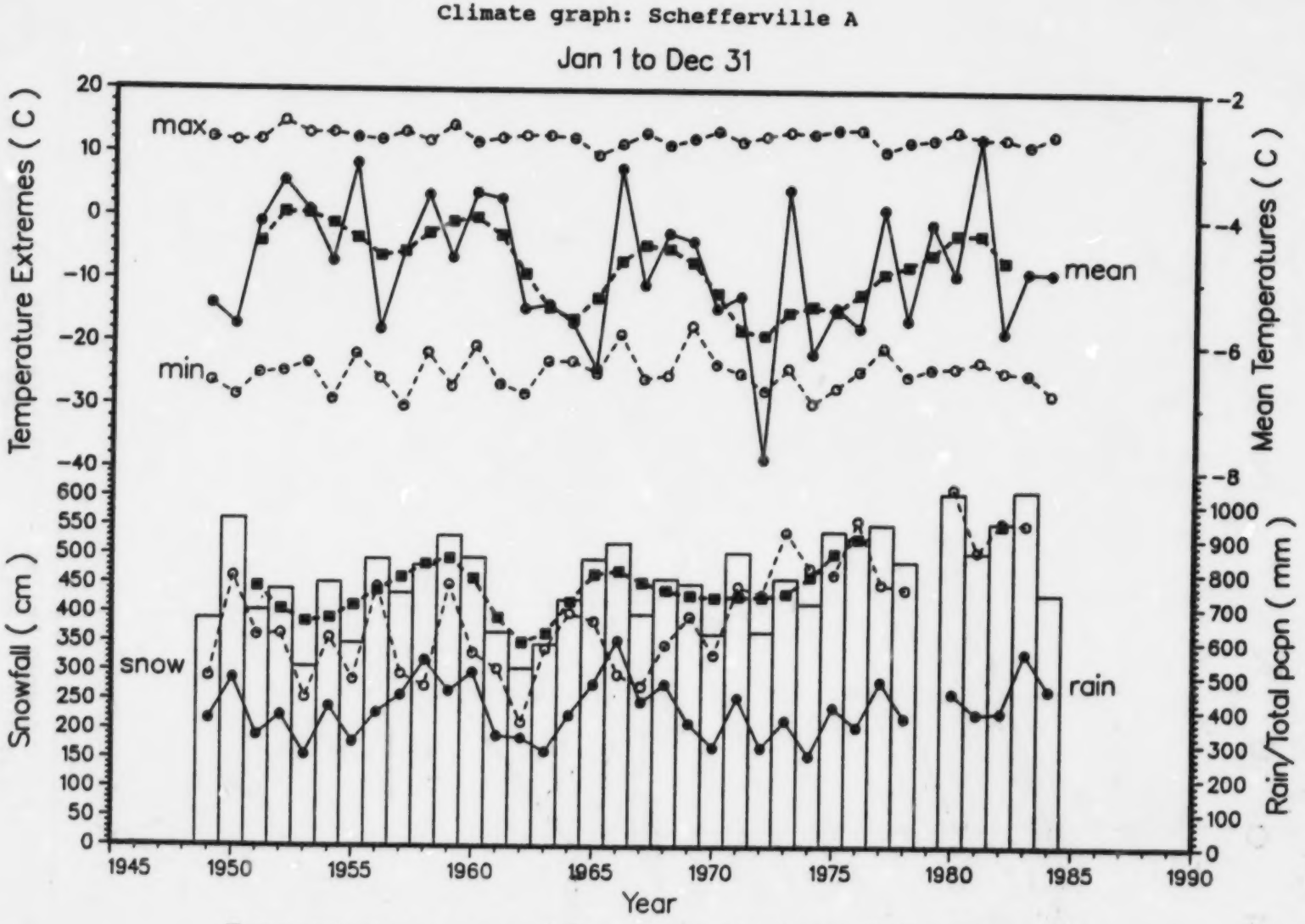
Figure 13a

Environmental hut



Side view of the hut housing the datalogger, tape recorder, and batteries. This design maintains a thermally stable environment.

Figure 13b



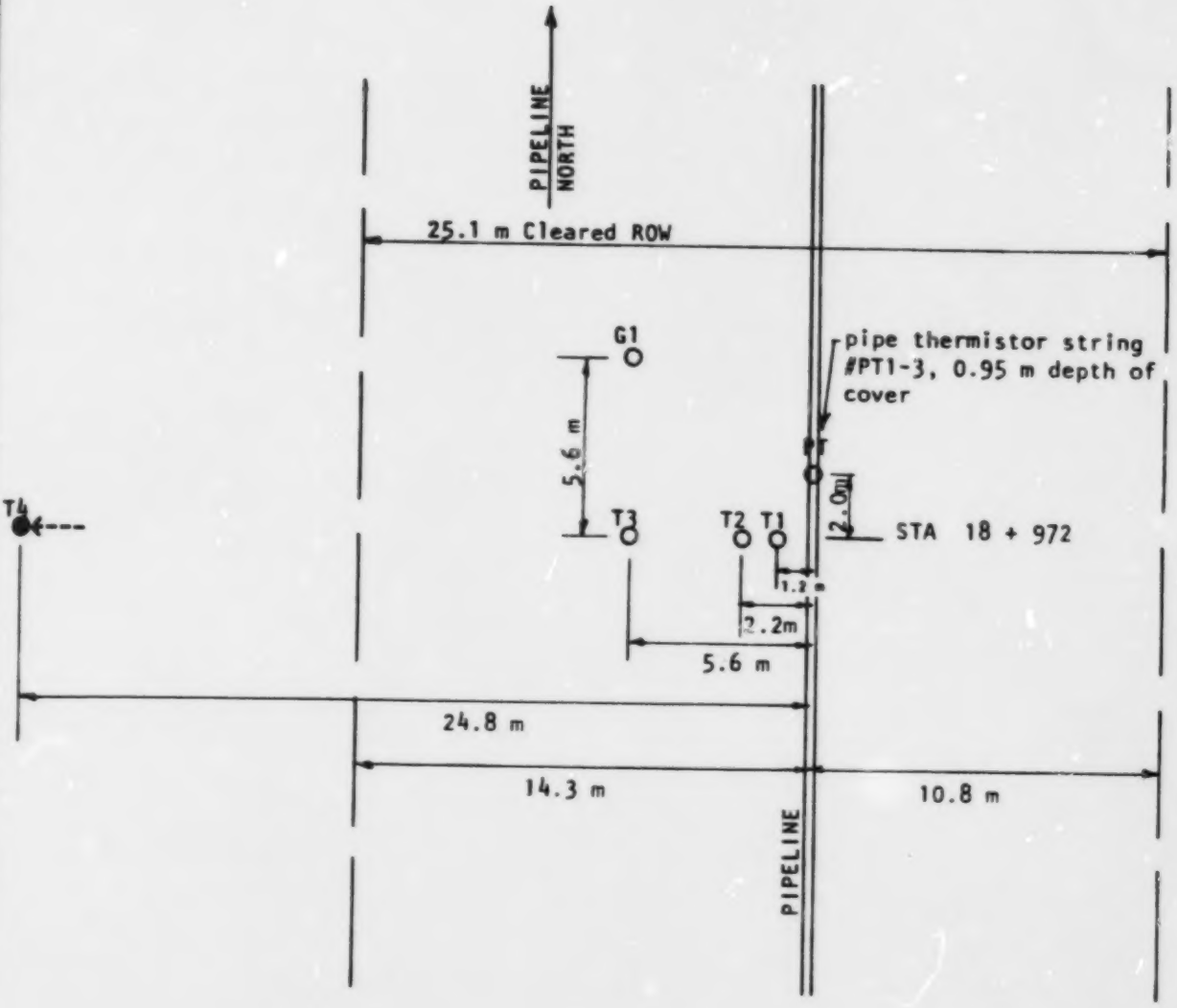
Temperature : mean = −4.8, st dev = 1.1, min = −24.7, max = 12.7
Precipitation means : rain = 399.9, snow = 398.4, total = 777.4

Figure 14

NORMAN WELLS

Norman Wells: topographical map
scale 1:250,000

Figure 15



ELEV RELATIVE TO T1 (TOP OF PVC)

HOLE	GROUND SURFACE	TOP OF PVC
T1	95.57 m	100.00 m
T2	99.57	99.90
T3	99.28	99.84
T4	98.75	99.18
G1	99.33	99.94

SCALE: 1:200

Figure 16

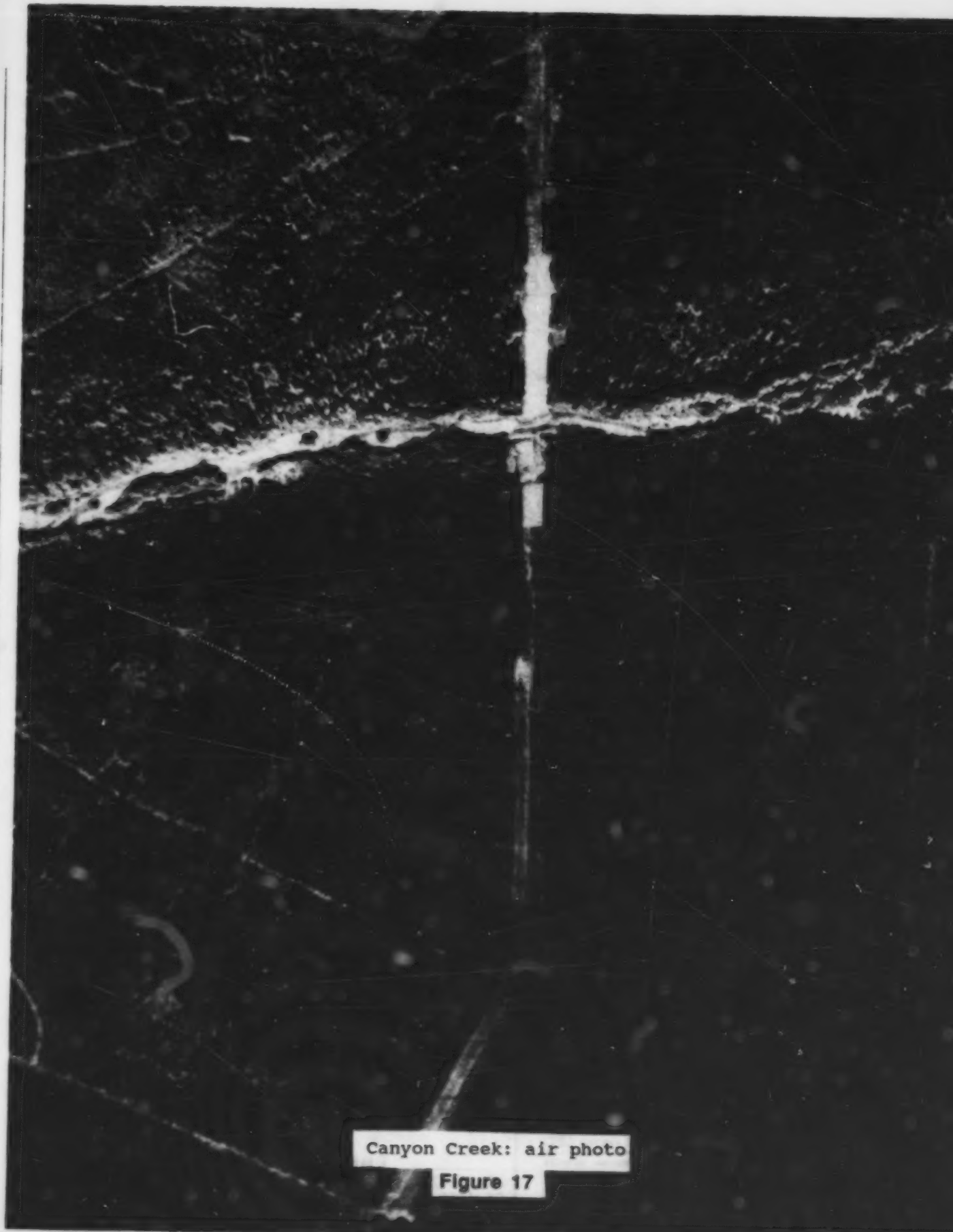
HARDY ASSOCIATES (1978) LTD.
CONSULTING ENGINEERING & PROFESSIONAL SERVICES

EMR INSTRUMENTATION PROGRAM
SITE PLAN
EMR-84-2a AT KP 18.9

CG 14056

PLATE A-2

HT09 79/05

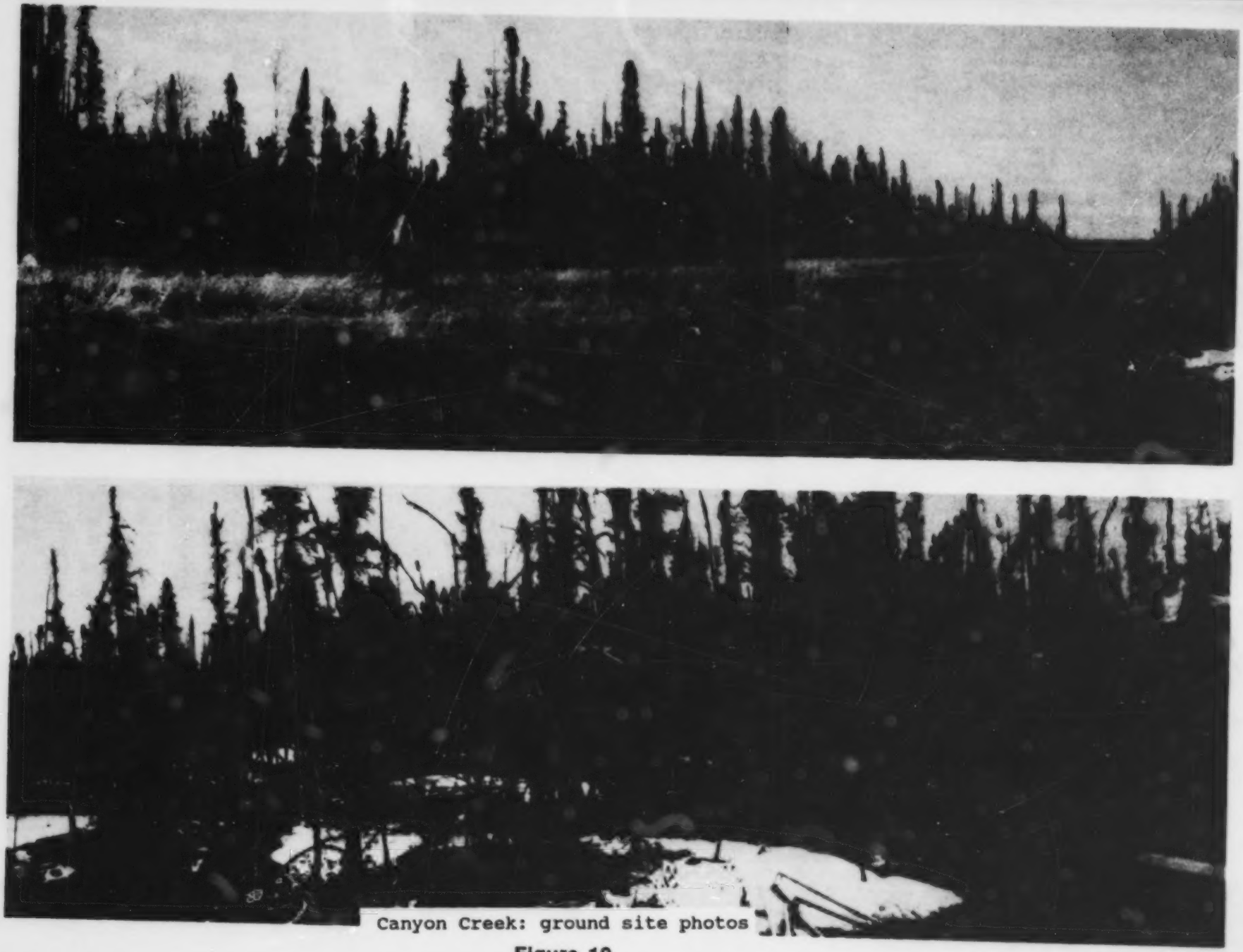


Canyon Creek: air photo

Figure 17

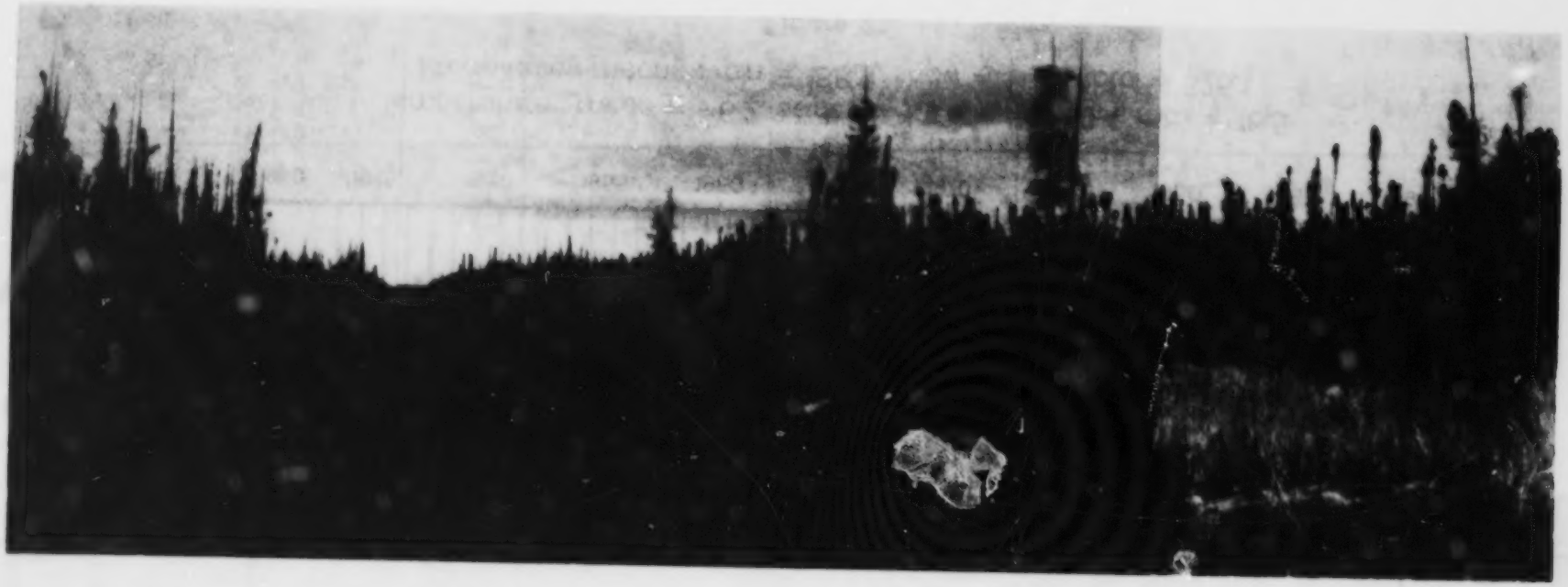
The pipeline at Canyon Creek, Nov. 1984.
photo by M. Burgess, EMR.

Figure 18



Canyon Creek: ground site photos

Figure 19



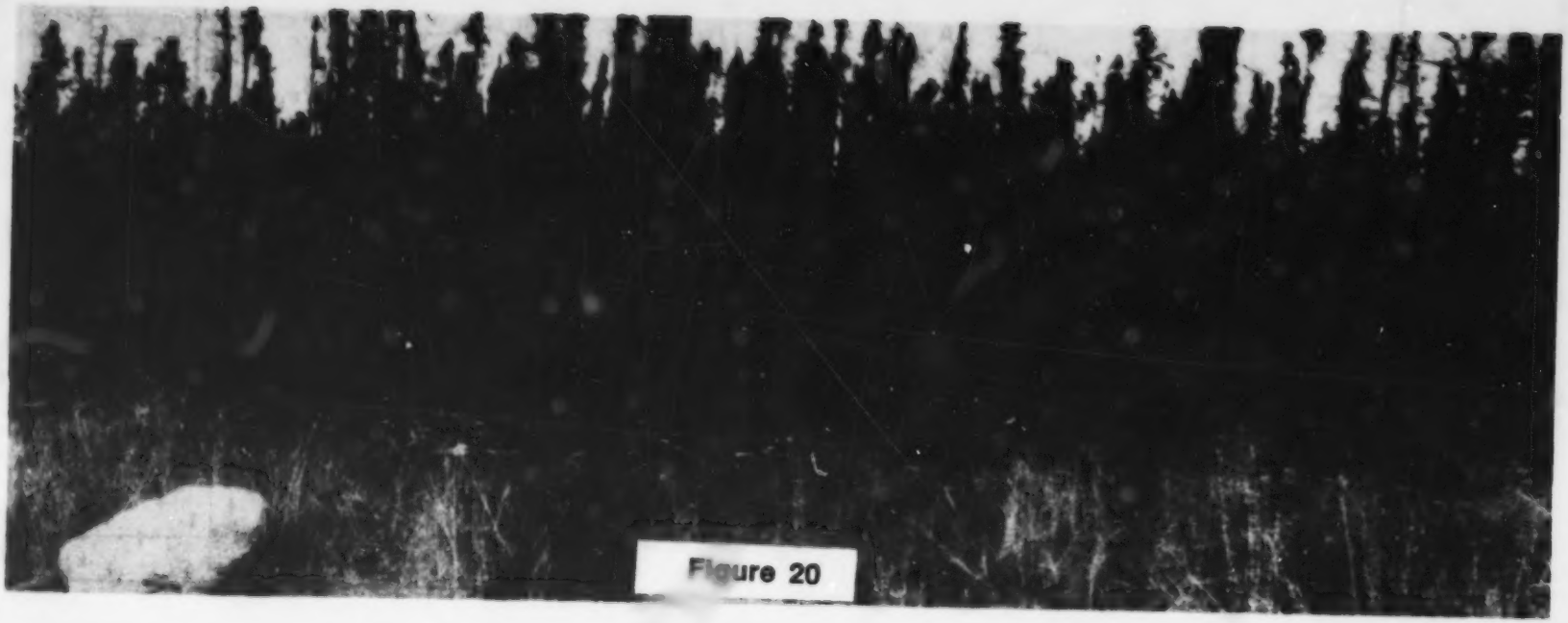
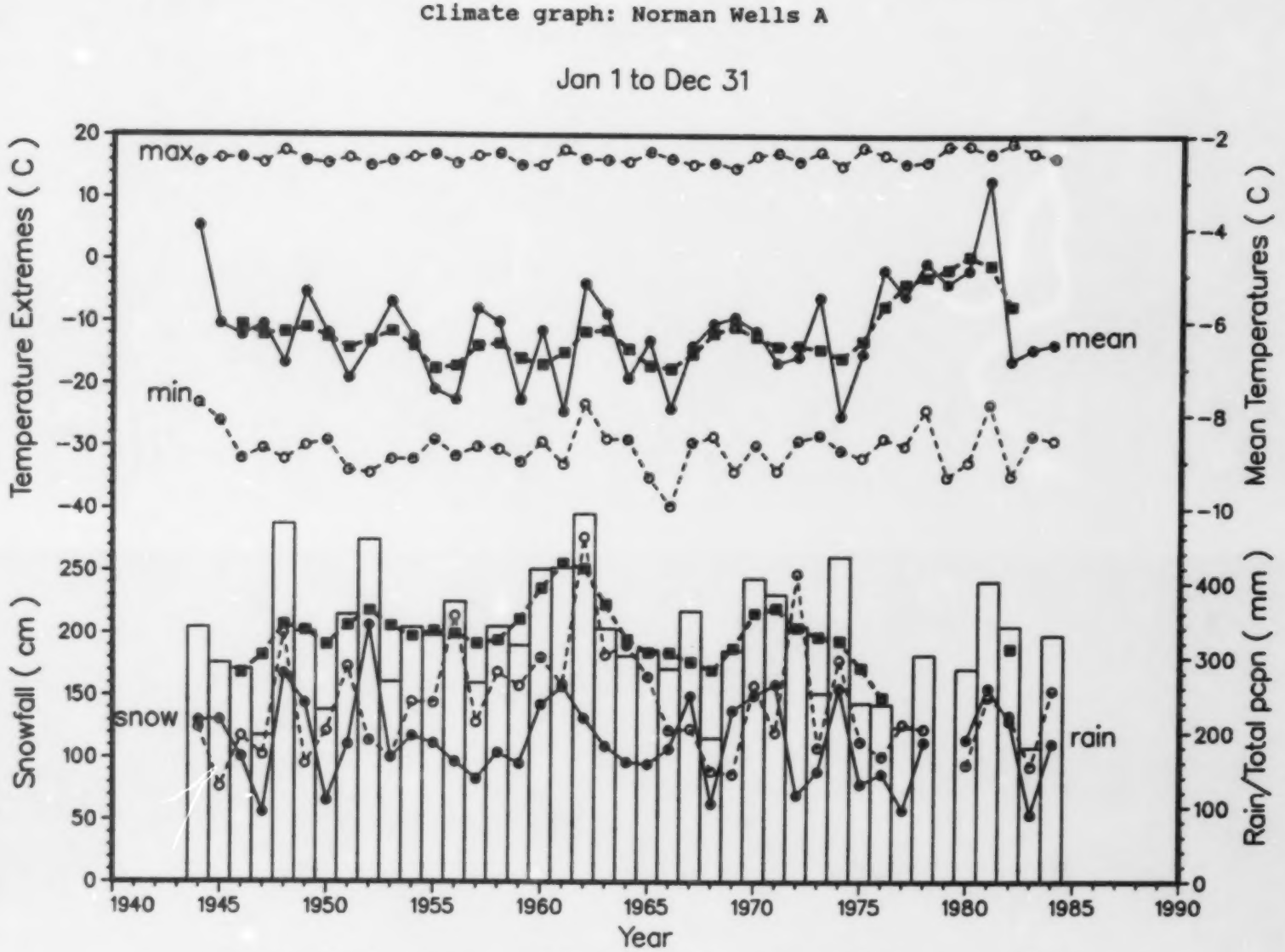


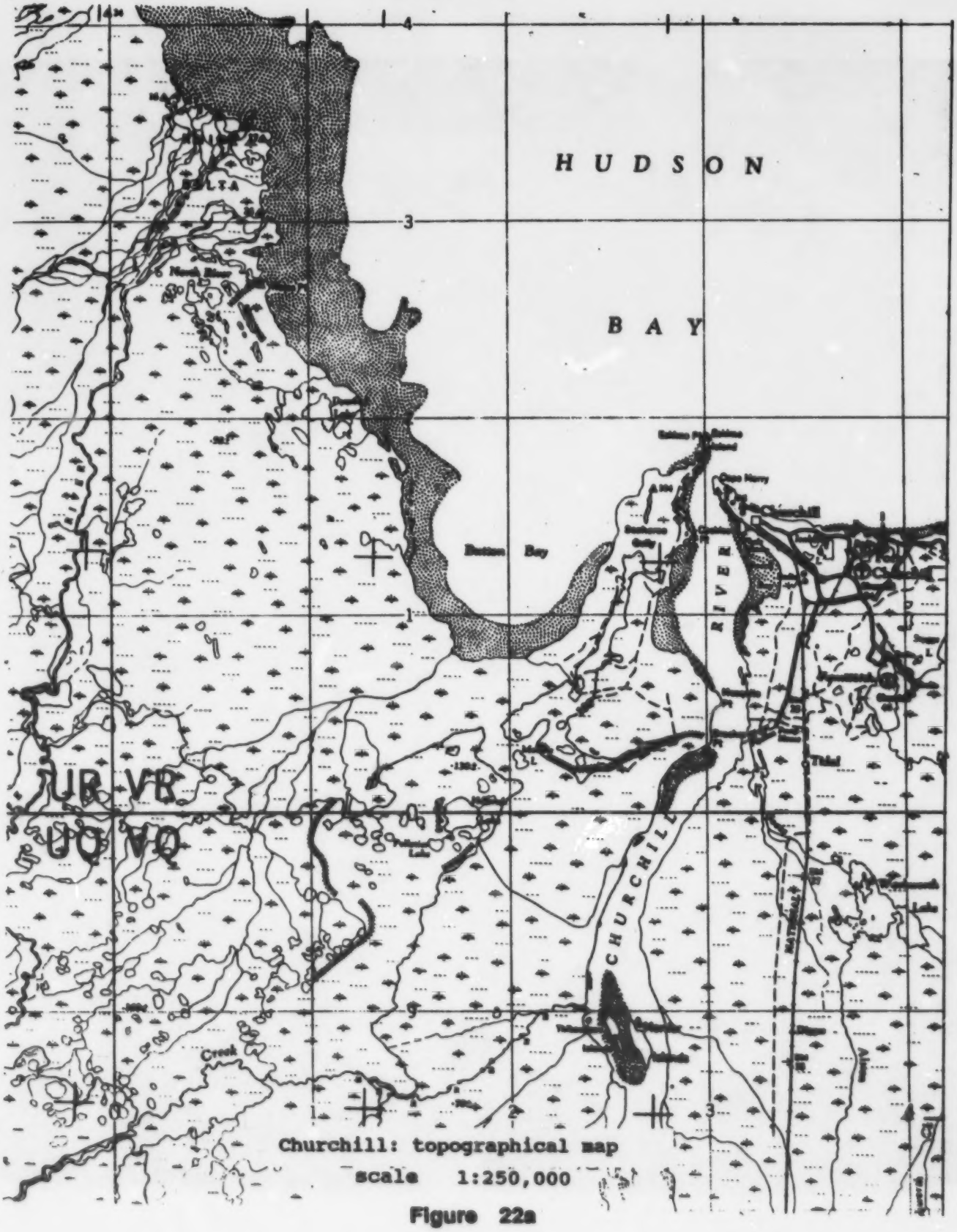
Figure 20



Temperature : mean = −6.2, st dev = 1.1, min = −30.4, max = 16.5
Precipitation means : rain = 188.9, snow = 141.5, total = 325.1

Figure 21

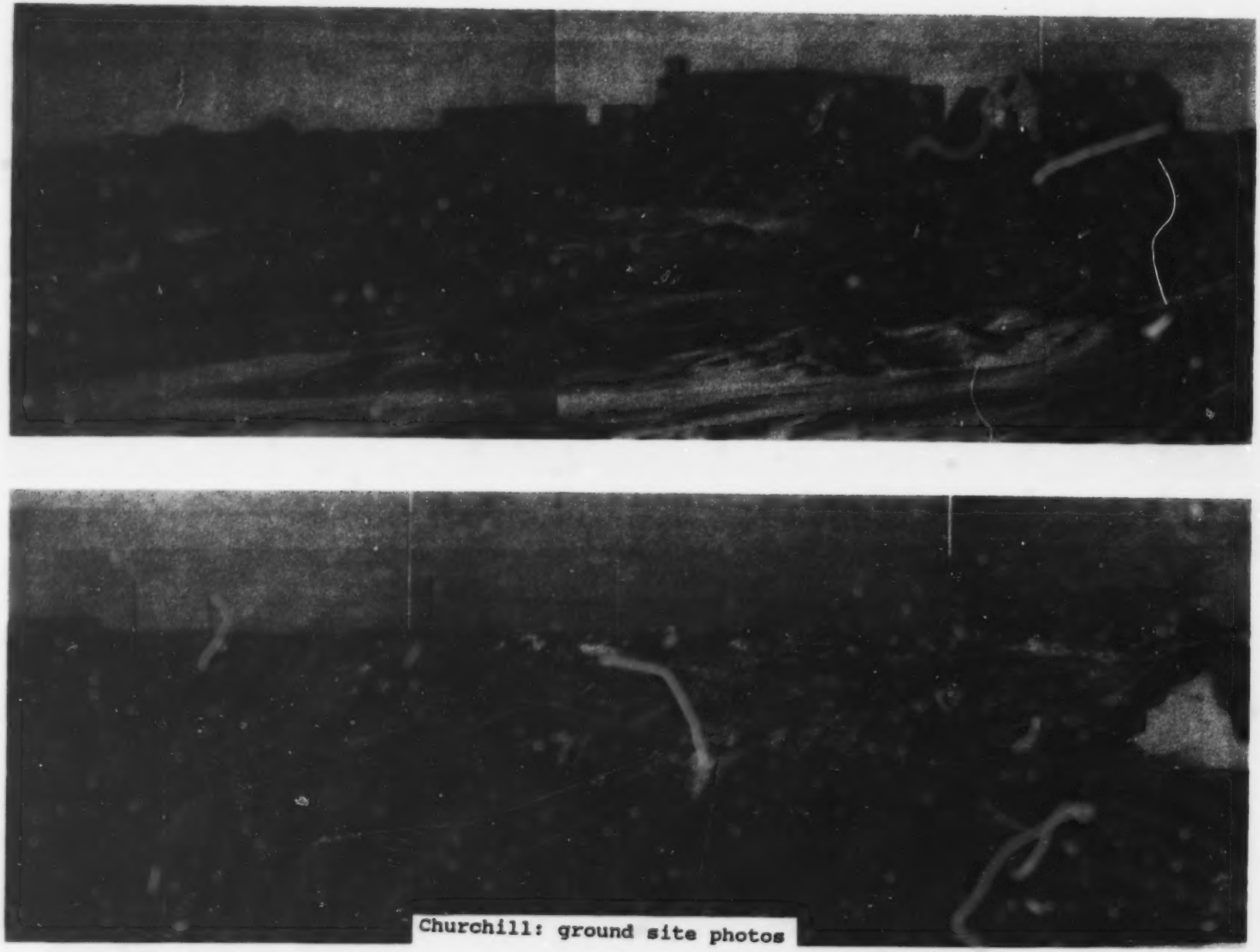
CHURCHILL



Churchill: topographical map
scale 1:250,000

Figure 22a

Churchill: air photo



Churchill: ground site photos

Figure 23

Figure 24

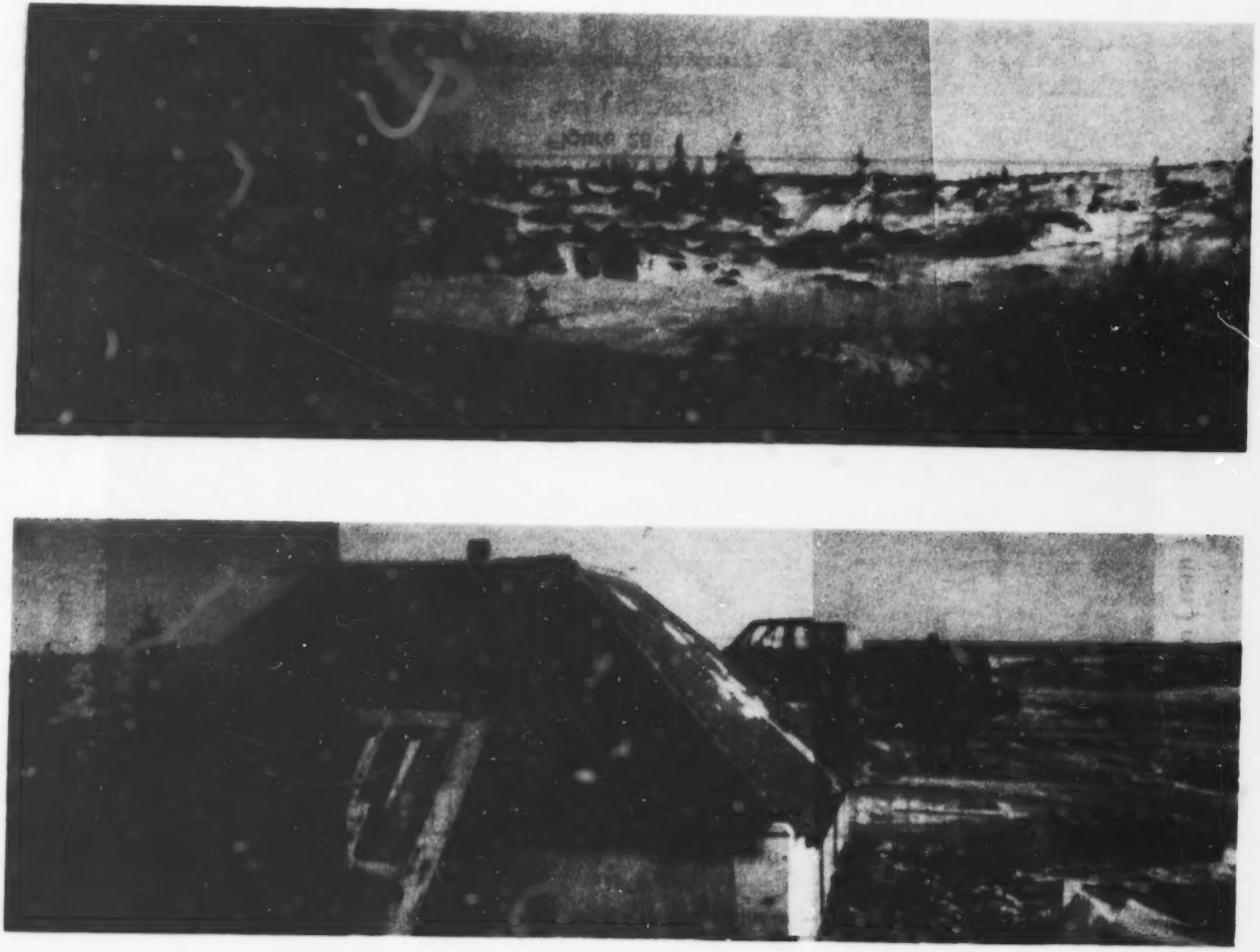


Figure 25

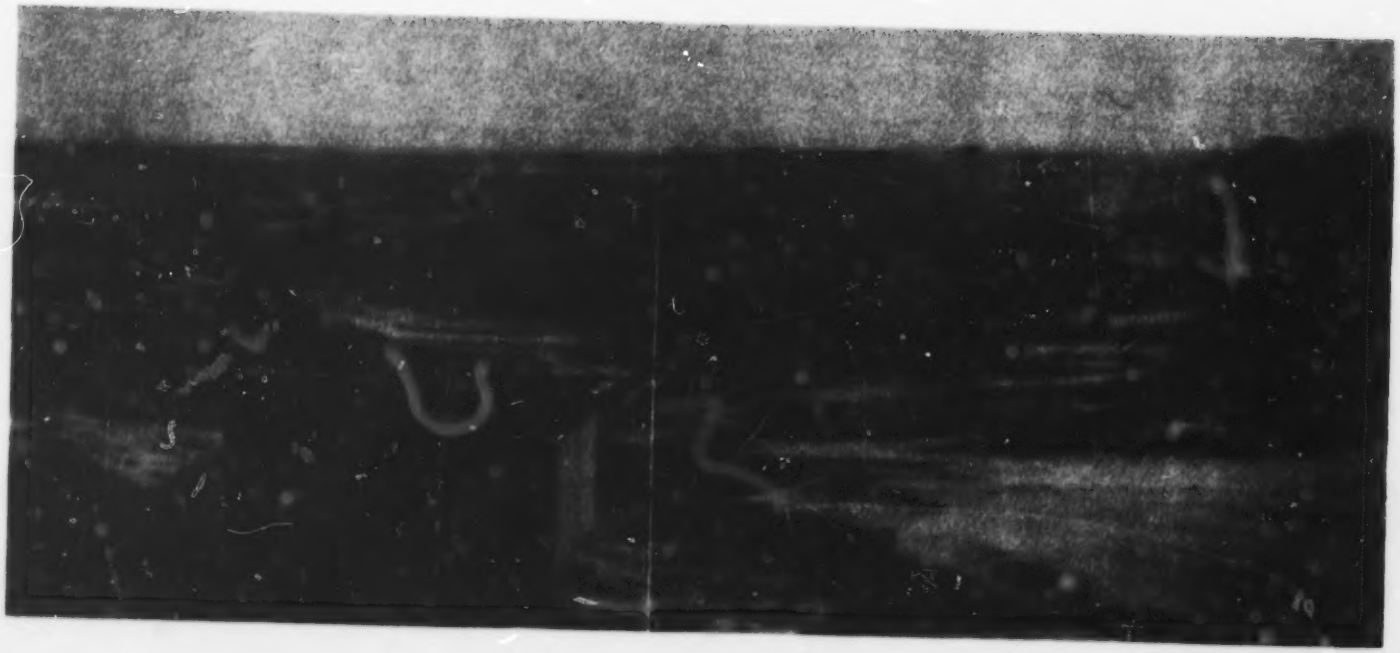
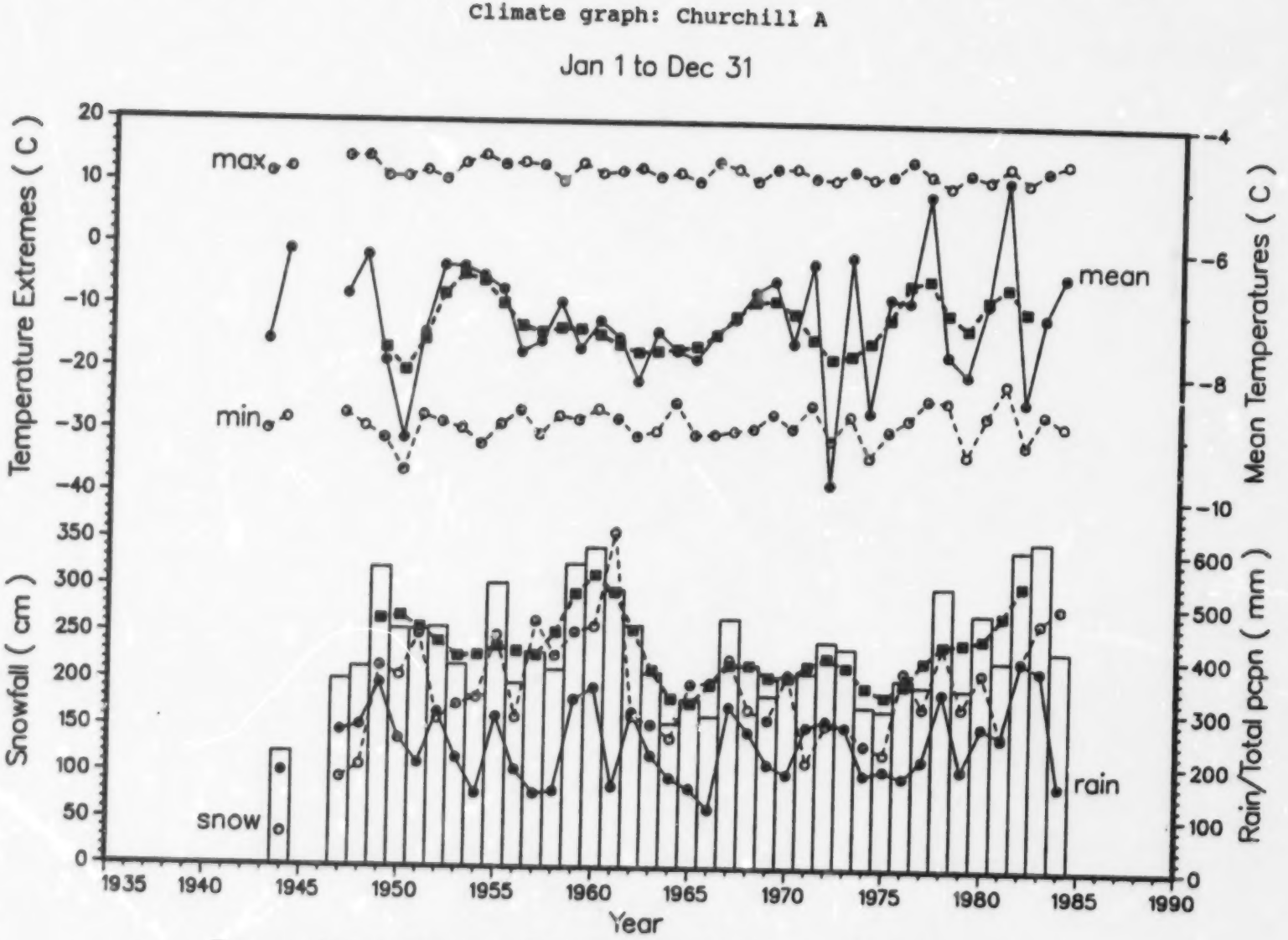


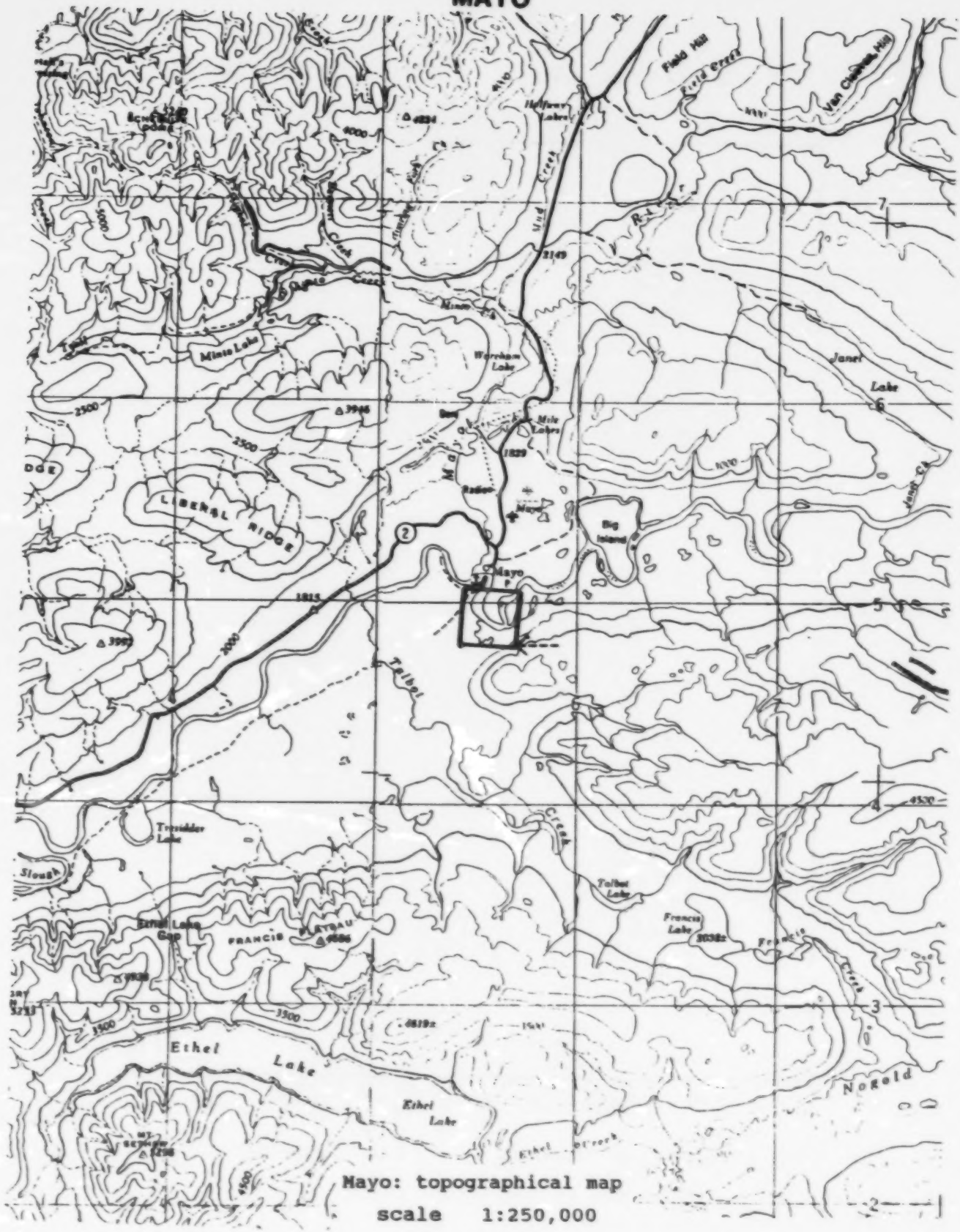
Figure 26



Temperature : mean = −7.2, st dev = 1.0, min = −28.6, max = 12.3
Precipitation means : rain = 233.4, snow = 190.9, total = 411.4

Figure 27

MAYO



Mayo: topographical map
scale 1:250,000

Figure 28

Location map, Mayo permafrost research site. Glacial and lacustrine sediment limits from Hughes (1983).

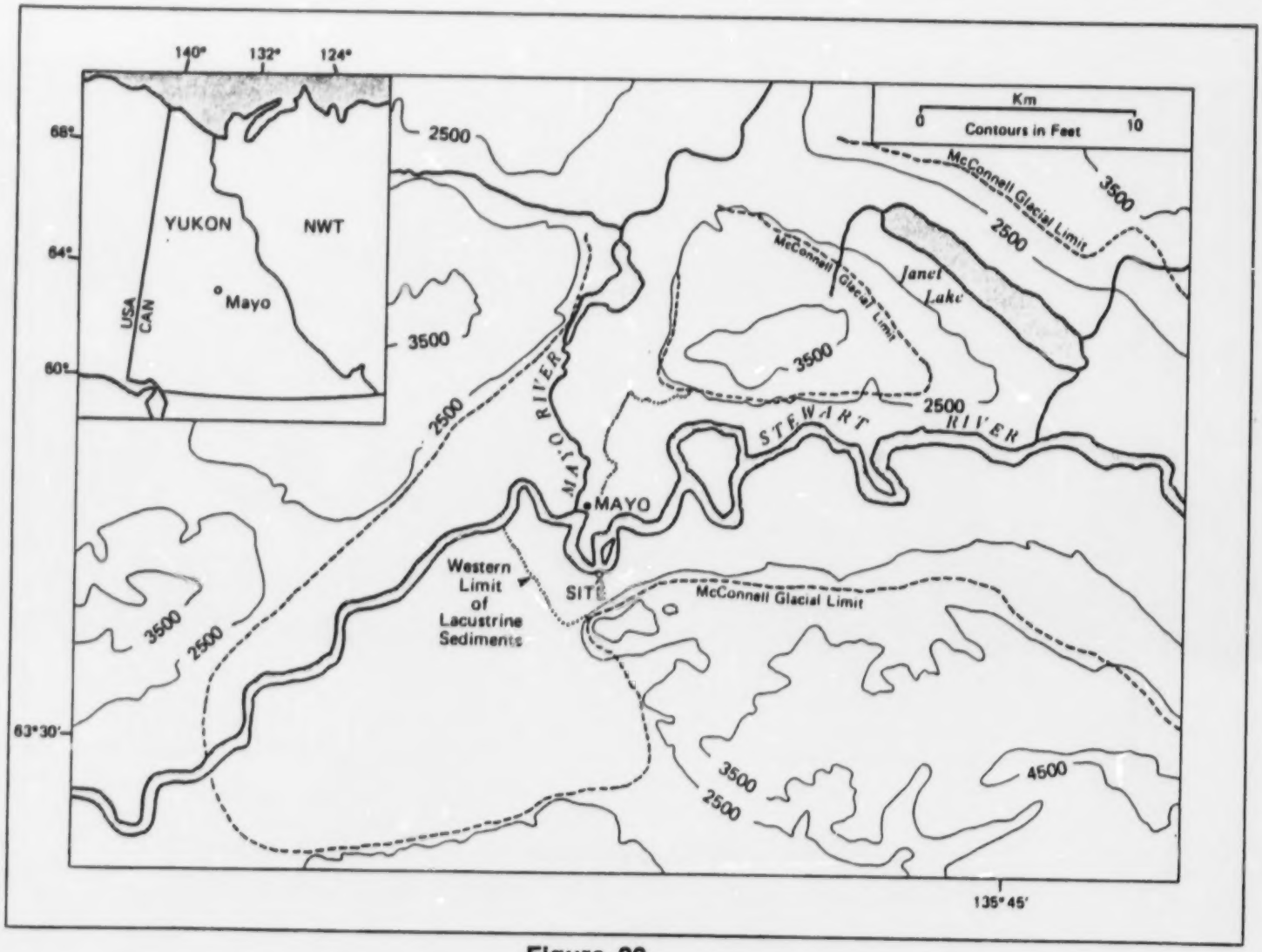
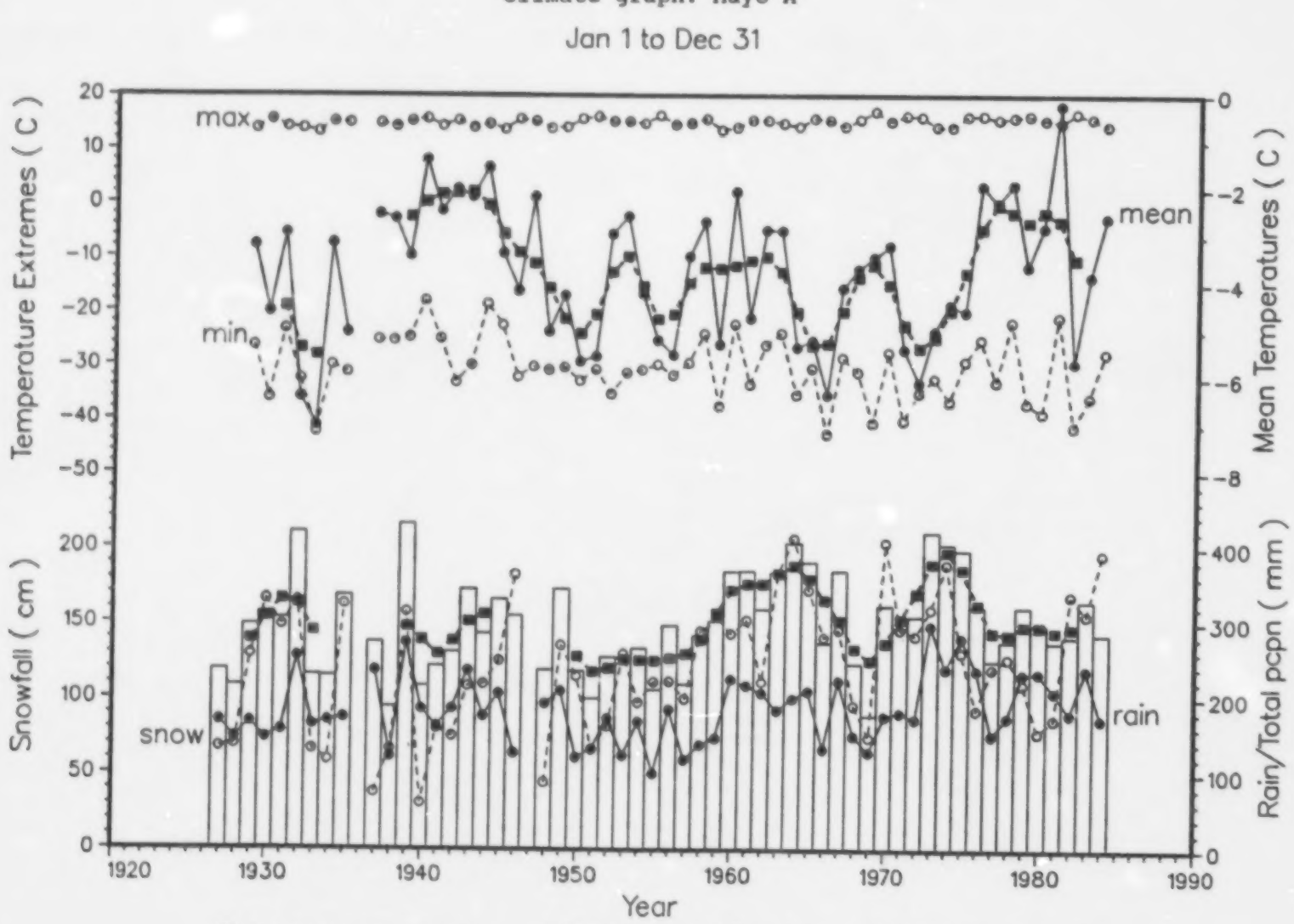


Figure 29



Temperature : mean = −3.7, st dev = 1.5, min = −30.6, max = 15.1
Precipitation means : rain = 184.7, snow = 121.8, total = 297.2

Figure 30

Mayo: air photos

Figure 31

Figure 32

Site 7.

Mayo: ground site photos

Figure 33

Site 6 in winter.

Figure 34

PROGRAM = DUMP9 : LISTING OF HOURLY PERMAFROST DATA : NORMAN WELLS

RUN

		THERMOCABLE 1 METRE DEGREES C	THERMOCABLE 2 METRE	AIR TEMP DEG C	RELATIVE HUMIDITY PERCENT	WIND SPEED KM/H	WIND DIRECTION DEGREES	PANEL TEMP DEG C
	16:00	-0.94	-0.42	-16.1	87	7.7	126	-1.2
	17:00	-0.94	-0.42	-16.7	86	8.9	145	-1.2
	18:00	-0.95	-0.42	-15.6	87	10.5	126	-1.2
	19:00	-0.96	-0.42	-14.4	85	14.6	128	-1.2
	20:00	-0.96	-0.43	-15.6	86	15.4	122	-1.2
	21:00	-0.97	-0.42	-15.6	86	21.4	156	-1.2
	22:00	-0.98	-0.42	-16.0	86	23.0	99	-1.2
	23:00	-0.98	-0.42	-15.8	85	25.6	107	-1.2
	24:00	-0.98	-0.42	-15.8	85	26.5	110	-1.2
DEC 6 86	1:00	-1.00	-0.42	-16.1	84	29.5	102	-1.2
	2:00	-1.00	-0.42	-16.8	83	30.2	106	-1.2
	3:00	-1.02	-0.42	-16.8	83	31.6	110	-1.2
	4:00	-1.03	-0.42	-16.6	83	33.7	128	-1.2
	5:00	-1.04	-0.42	-16.8	83	33.6	97	-1.2
	6:00	-1.04	-0.42	-17.1	82	34.6	104	-1.2
	7:00	-1.06	-0.42	-17.1	82	33.1	105	-1.2
	8:00	-1.06	-0.42	-16.9	81	33.1	114	-1.2
	9:00	-1.06	-0.42	-16.6	80	33.7	100	-1.2
	10:00	-1.06	-0.42	-16.1	80	30.8	105	-1.2
	11:00	-1.04	-0.42	-15.8	80	31.2	101	-1.2
	12:00	-1.04	-0.42	-15.4	79	30.2	111	-1.2
	13:00	-1.02	-0.42	-14.6	79	28.9	95	-1.2
	14:00	-1.00	-0.42	-14.3	79	29.0	123	-1.2
	15:00	-0.98	-0.42	-14.3	78	28.3	142	-1.2
	16:00	-0.98	-0.42	-14.3	78	27.6	101	-1.2
	17:00	-0.98	-0.42	-14.4	78	23.8	130	-1.2
	18:00	-0.98	-0.42	-14.6	77	19.3	81	-1.2
	19:00	-0.98	-0.42	-14.9	78	16.5	95	-1.2
	20:00	-0.98	-0.42	-14.9	78	15.0	112	-1.2
	21:00	-0.98	-0.42	-15.0	78	13.0	120	-1.2
	22:00	-0.98	-0.42	-15.0	78	9.3	123	-1.2
	23:00	-0.96	-0.42	-14.7	78	5.8	137	-1.2
	24:00	-0.93	-0.42	-14.6	80	2.6	182	-1.1
DEC 7 86	1:00	-0.91	-0.42	-14.7	81	0.1	307	-1.1
	2:00	-0.90	-0.42	-14.8	82	7.0	300	-1.1
	3:00	-0.90	-0.42	-14.9	84	7.6	299	-1.1
	4:00	-0.90	-0.42	-15.3	86	7.4	286	-1.1
	5:00	-0.91	-0.42	-15.3	87	10.4	274	-1.1
	6:00	-0.92	-0.42	-15.8	86	11.1	298	-1.1
	7:00	-0.93	-0.42	-16.2	86	11.6	274	-1.1
	8:00	-0.94	-0.42	-15.9	87	8.4	278	-1.1
	9:00	-0.92	-0.43	-15.3	88	6.6	250	-1.1
	10:00	-0.90	-0.42	-14.3	89	7.6	281	-1.1
	11:00	-0.88	-0.42	-12.9	91	8.9	308	-1.1
	12:00	-0.86	-0.42	-12.9	91	9.9	265	-1.1
	13:00	-0.85	-0.42	-10.7	93	12.1	297	-1.1
	14:00	-0.81	-0.42	-9.2	94	12.0	267	-1.1
	15:00	-0.76	-0.42	-9.1	94	8.4	297	-1.1
	16:00	-0.74	-0.42	-10.4	94	7.7	320	-1.1
	17:00	-0.76	-0.42	-10.7	94	6.6	346	-1.1
	18:00	-0.78	-0.42	-9.6	95	8.6	326	-1.1
	19:00	-0.77	-0.42	-10.1	95	6.0	357	-1.1

Table 2

PROGRAM = DUMP13 : LISTING OF DAILY PERMAFROST DATA : NORMAN WELLS

RUN DATE 25/02/87

	THERMOCABLE DEGREES C									RAIN	SOIL MOIST	BATTERY VOLTAGE	SNOW DEPTH
	3 M	4 M	5 M	6 M	7 M	8 M	9 M	11 M	13 M	MM	BARS	VOLTS	CM
DEC 18 86	-0.62	-0.41	-0.87	-0.87	-0.97	-0.93	-0.99	-0.99	-0.89	0.0	+6999.	12.56	43
DEC 19 86	-0.62	-0.41	-0.87	-0.87	-0.97	-0.93	-0.99	-0.99	-0.89	0.0	+6999.	12.56	42
DEC 20 86	-0.62	-0.41	-0.87	-0.87	-0.97	-0.93	-0.99	-0.99	-0.89	0.0	+6999.	12.56	41
DEC 21 86	-0.61	-0.41	-0.87	-0.87	-0.96	-0.93	-0.99	-0.99	-0.89	0.0	+6999.	12.56	31
DEC 22 86	-0.61	-0.41	-0.87	-0.86	-0.96	-0.93	-0.99	-0.99	-0.89	0.0	+6999.	12.55	43
DEC 23 86	-0.61	-0.41	-0.87	-0.86	-0.96	-0.92	-0.99	-0.99	-0.89	0.0	+6999.	12.55	43
DEC 24 86	-0.61	-0.40	-0.87	-0.86	-0.96	-0.92	-0.99	-0.98	-0.89	0.0	+6999.	12.55	46
DEC 25 86	-0.61	-0.40	-0.86	-0.86	-0.96	-0.92	-0.98	-0.98	-0.89	0.0	+6999.	12.54	45
DEC 26 86	-0.61	-0.40	-0.86	-0.86	-0.96	-0.92	-0.98	-0.98	-0.89	0.0	+6999.	12.54	45
DEC 27 86	-0.61	-0.40	-0.86	-0.86	-0.96	-0.92	-0.98	-0.98	-0.89	0.0	+6999.	12.54	40
DEC 28 86	-0.61	-0.39	-0.86	-0.86	-0.95	-0.92	-0.98	-0.99	-0.89	0.0	+6999.	12.52	48
DEC 29 86	-0.61	-0.39	-0.86	-0.86	-0.96	-0.92	-0.98	-0.99	-0.89	0.0	+6999.	12.53	52
DEC 30 86	-0.61	-0.39	-0.86	-0.86	-0.96	-0.92	-0.98	-0.99	-0.90	0.0	+6999.	12.53	53
DEC 31 86	-0.61	-0.38	-0.86	-0.86	-0.96	-0.92	-0.98	-0.99	-0.90	0.0	+6999.	12.53	56
JAN 1 87	-0.61	-0.38	-0.86	-0.86	-0.96	-0.92	-0.98	-0.99	-0.90	0.0	+6999.	12.52	58
JAN 2 87	-0.60	-0.38	-0.86	-0.86	-0.95	-0.92	-0.98	-0.99	-0.89	0.0	+6999.	12.52	58
JAN 3 87	-0.60	-0.38	-0.86	-0.86	-0.95	-0.91	-0.98	-0.99	-0.90	0.0	+6999.	12.52	55
JAN 4 87	-0.60	-0.37	-0.85	-0.85	-0.95	-0.91	-0.98	-0.99	-0.89	0.0	+6999.	12.52	55
JAN 5 87	-0.60	-0.37	-0.85	-0.85	-0.95	-0.92	-0.98	-0.99	-0.89	0.0	+6999.	12.51	54
JAN 6 87	-0.60	-0.37	-0.85	-0.85	-0.95	-0.91	-0.98	-0.99	-0.89	0.0	+6999.	12.51	54
JAN 7 87	-0.60	-0.37	-0.85	-0.85	-0.95	-0.91	-0.98	-0.99	-0.89	0.0	+6999.	12.51	51
JAN 8 87	-0.60	-0.36	-0.85	-0.85	-0.95	-0.91	-0.98	-0.99	-0.89	0.0	+6999.	12.51	55
JAN 9 87	-0.60	-0.36	-0.85	-0.85	-0.95	-0.91	-0.97	-0.99	-0.89	0.0	+6999.	12.51	55
JAN 10 87	-0.60	-0.36	-0.85	-0.85	-0.95	-0.91	-0.98	-0.99	-0.89	0.0	+6999.	12.51	55
JAN 11 87	-0.59	-0.35	-0.85	-0.85	-0.95	-0.91	-0.98	-0.99	-0.89	0.0	+6999.	12.50	55
JAN 12 87	-0.59	-0.35	-0.85	-0.85	-0.95	-0.91	-0.97	-0.99	-0.89	0.0	+6999.	12.50	55
JAN 13 87	-0.59	-0.35	-0.85	-0.85	-0.95	-0.91	-0.98	-0.99	-0.89	0.0	+6999.	12.50	54
JAN 14 87	-0.60	-0.35	-0.85	-0.85	-0.95	-0.91	-0.98	-0.99	-0.89	0.0	+6999.	12.53	54
JAN 15 87	-0.60	-0.35	-0.85	-0.84	-0.95	-0.91	-0.98	-0.98	-0.89	0.0	+6999.	12.50	55
JAN 16 87	-0.59	-0.35	-0.84	-0.85	-0.95	-0.91	-0.97	-0.99	-0.89	0.0	+6999.	12.50	55
JAN 17 87	-0.59	-0.35	-0.84	-0.85	-0.95	-0.91	-0.98	-0.99	-0.89	0.0	+6999.	12.49	56
JAN 18 87	-0.59	-0.34	-0.84	-0.84	-0.94	-0.91	-0.97	-0.99	-0.89	0.0	+6999.	12.49	53
JAN 19 87	-0.59	-0.34	-0.84	-0.84	-0.94	-0.91	-0.97	-0.98	-0.89	0.0	+6999.	12.49	54
JAN 20 87	-0.59	-0.34	-0.83	-0.84	-0.94	-0.91	-0.97	-0.98	-0.89	0.0	+6999.	12.56	107
JAN 21 87	-0.59	-0.33	-0.83	-0.84	-0.94	-0.91	-0.97	-0.98	-0.89	0.0	+6999.	12.56	53
JAN 22 87	-0.59	-0.33	-0.83	-0.84	-0.94	-0.91	-0.97	-0.98	-0.89	0.0	+6999.	12.58	53
JAN 23 87	-0.59	-0.33	-0.83	-0.84	-0.94	-0.91	-0.97	-0.98	-0.89	0.0	+6999.	12.61	52
JAN 24 87	-0.59	-0.33	-0.83	-0.84	-0.94	-0.91	-0.97	-0.98	-0.89	0.0	+6999.	12.61	118
JAN 25 87	-0.59	-0.33	-0.83	-0.84	-0.93	-0.91	-0.97	-0.98	-0.89	0.0	+6999.	12.54	51
JAN 26 87	-0.59	-0.33	-0.83	-0.84	-0.93	-0.90	-0.97	-0.98	-0.89	0.0	+6999.	12.51	51
JAN 27 87	-0.59	-0.32	-0.83	-0.83	-0.93	-0.90	-0.97	-0.98	-0.89	0.0	+6999.	12.50	52
JAN 28 87	-0.59	-0.32	-0.83	-0.84	-0.93	-0.90	-0.97	-0.98	-0.89	0.0	+6999.	12.52	57
JAN 29 87	-0.59	-0.32	-0.83	-0.84	-0.93	-0.91	-0.97	-0.98	-0.89	0.0	+6999.	12.49	57
JAN 30 87	-0.58	-0.32	-0.83	-0.83	-0.93	-0.91	-0.97	-0.98	-0.89	0.0	+6999.	12.58	56
JAN 31 87	-0.58	-0.31	-0.82	-0.83	-0.93	-0.90	-0.97	-0.98	-0.89	0.0	+6999.	12.53	55
FEB 1 87	-0.58	-0.31	-0.83	-0.83	-0.93	-0.90	-0.97	-0.98	-0.89	0.0	+6999.	12.50	55
FEB 2 87	-0.58	-0.31	-0.82	-0.83	-0.93	-0.90	-0.97	-0.98	-0.90	0.0	+6999.	12.62	55
FEB 3 87	-0.58	-0.30	-0.82	-0.83	-0.93	-0.90	-0.97	-0.98	-0.90	0.0	+6999.	12.68	56
FEB 4 87	-0.58	-0.30	-0.82	-0.83	-0.93	-0.90	-0.97	-0.98	-0.90	0.0	+6999.	12.60	54
FEB 5 87	-0.58	-0.30	-0.82	-0.83	-0.93	-0.90	-0.97	-0.98	-0.90	0.0	+6999.	12.56	59

Table 3

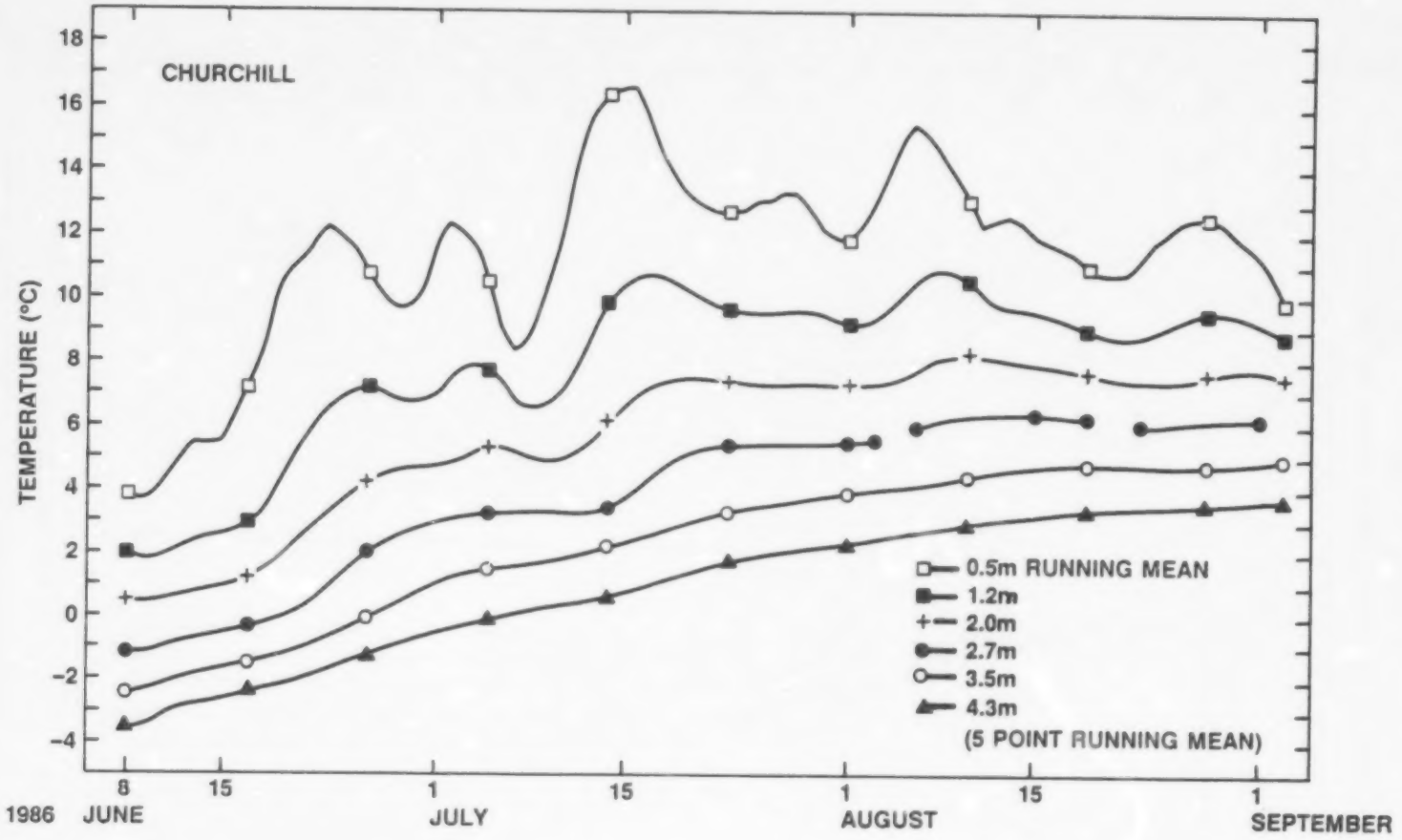

CHURCHILL
TEMPERATURE (°C)
18
16
14
12
10
8
6
4
2
0
-2
-4
0.5m RUNNING MEAN
1.2m
2.0m
2.7m
3.5m
4.3m
(5 POINT RUNNING MEAN)
1986 JUNE
8
15
JULY
1
15
AUGUST
1
15
SEPTEMBER
1

Figure 35

Ground Temperatures

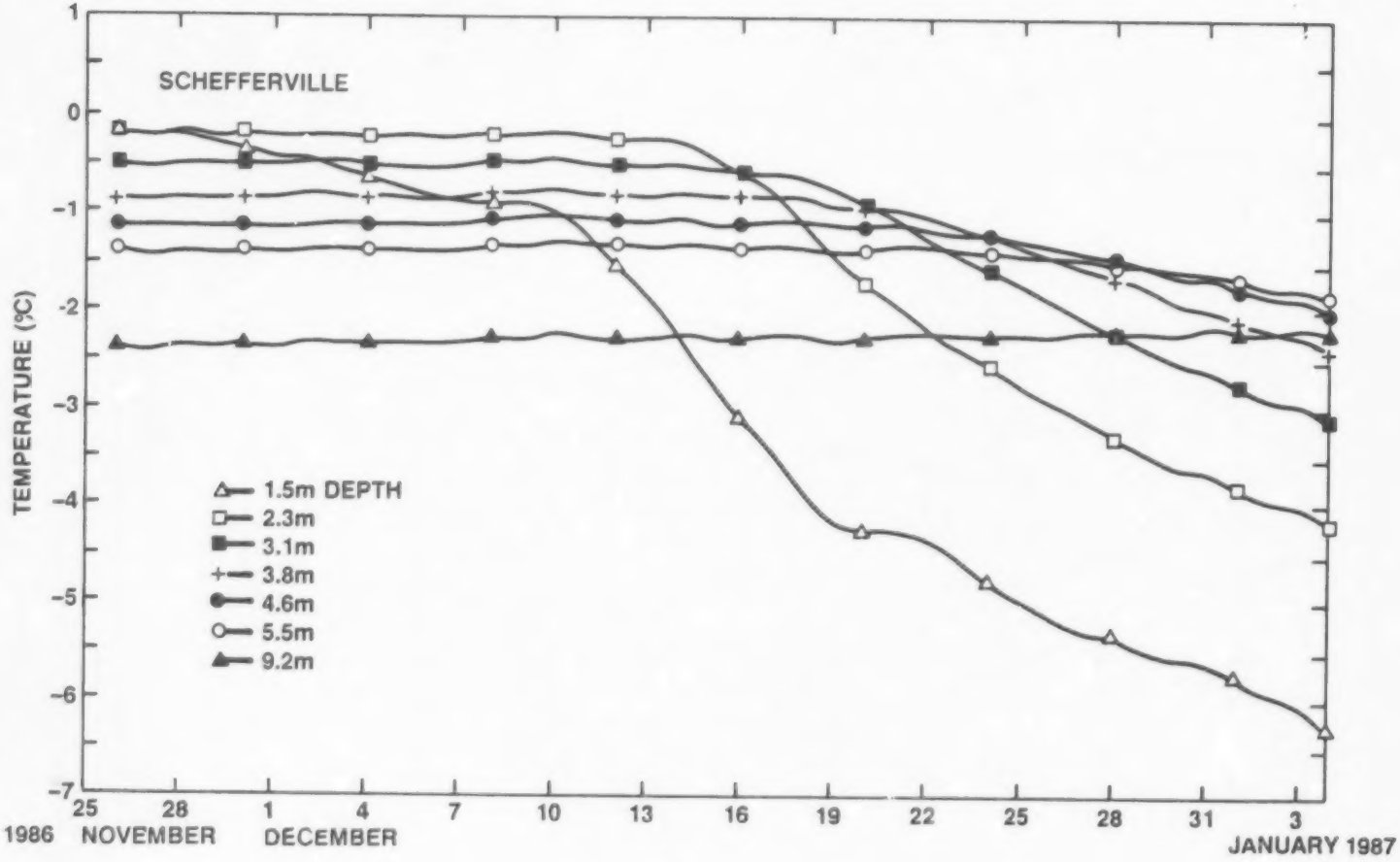


Figure 36

Permafrost Climate Project
Depth Graphs
Jan 1, 1986 – Apr 1, 1987, Location : Churchill

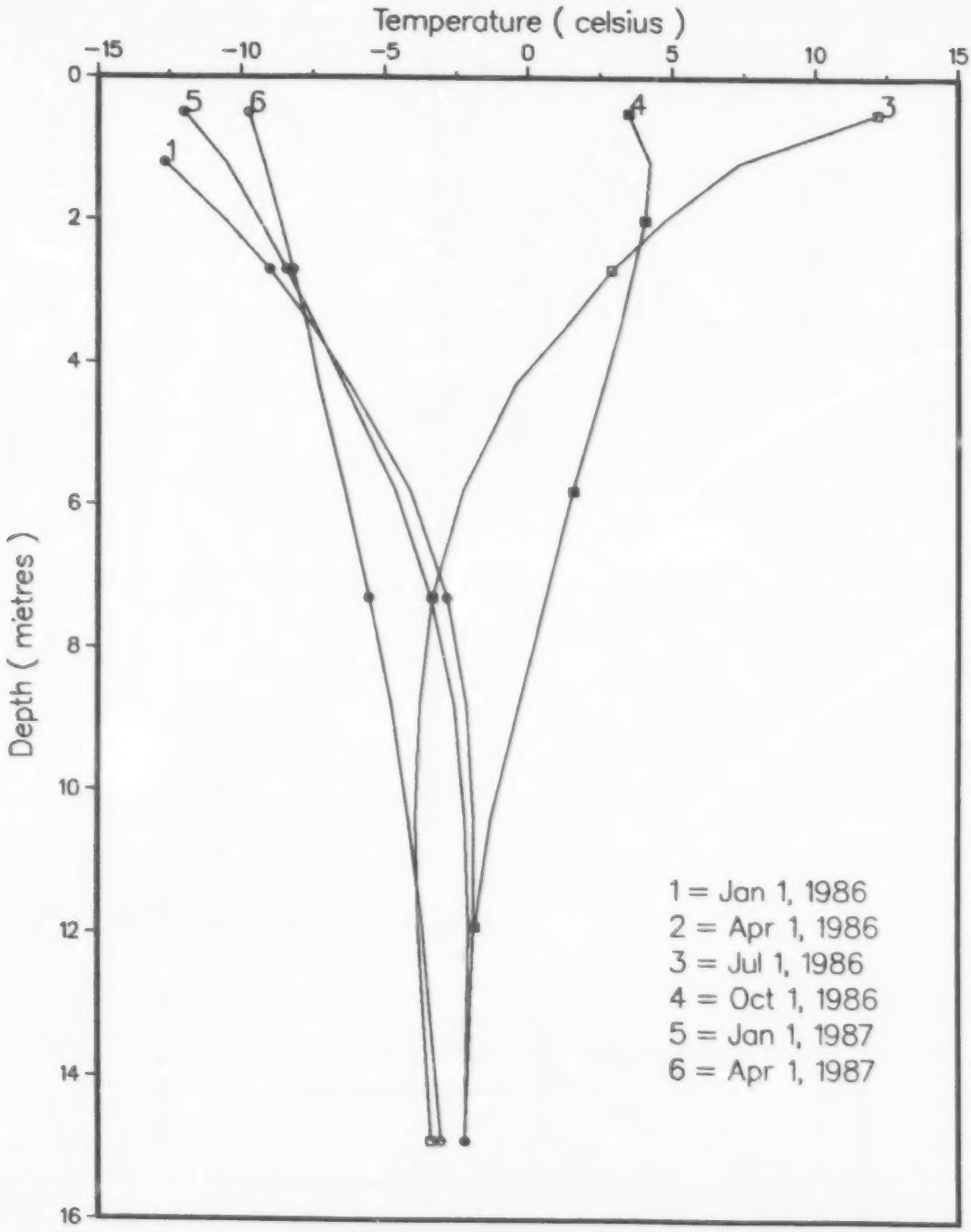


Figure 37

Temperature Envelope Graph

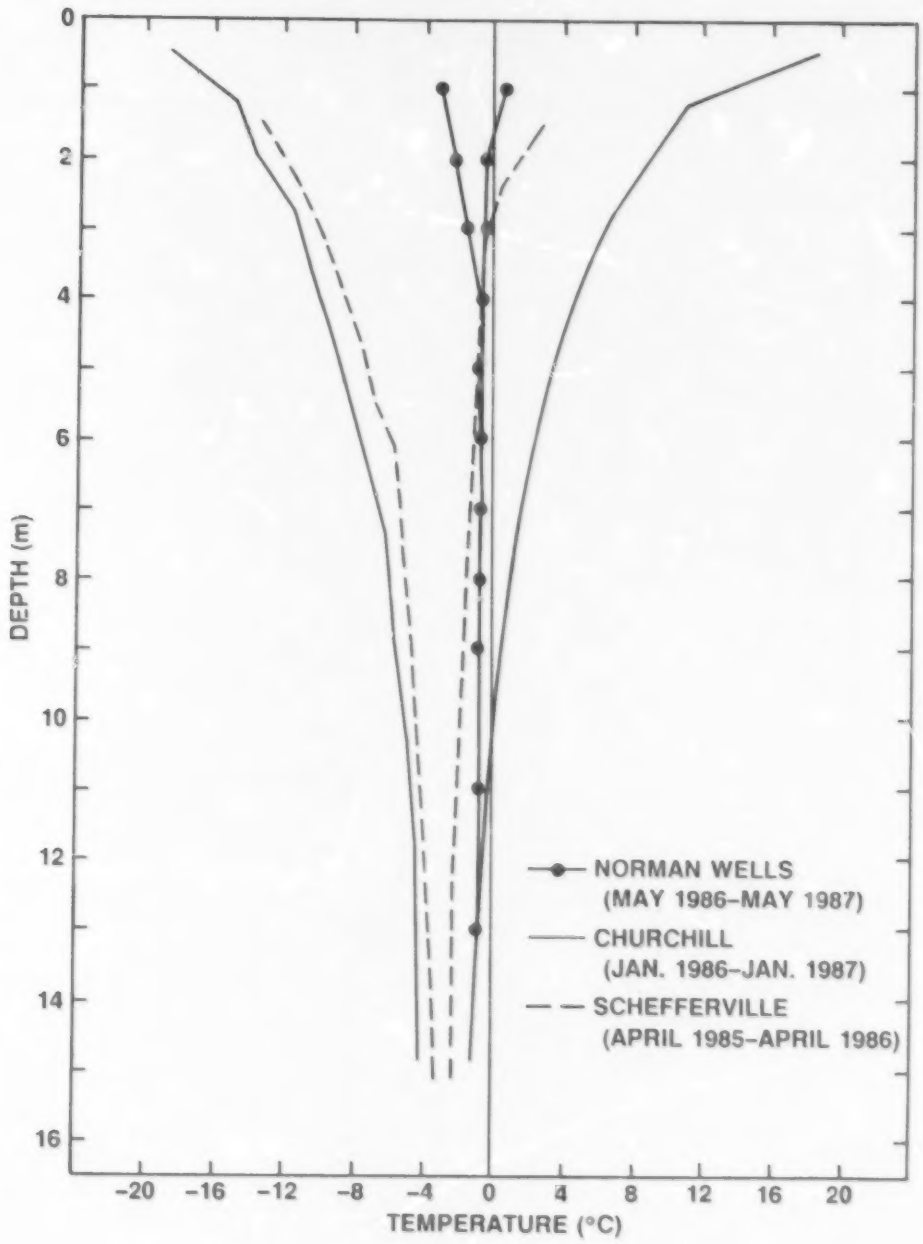


Figure 38

Time-Series of Air & Ground Temperatures

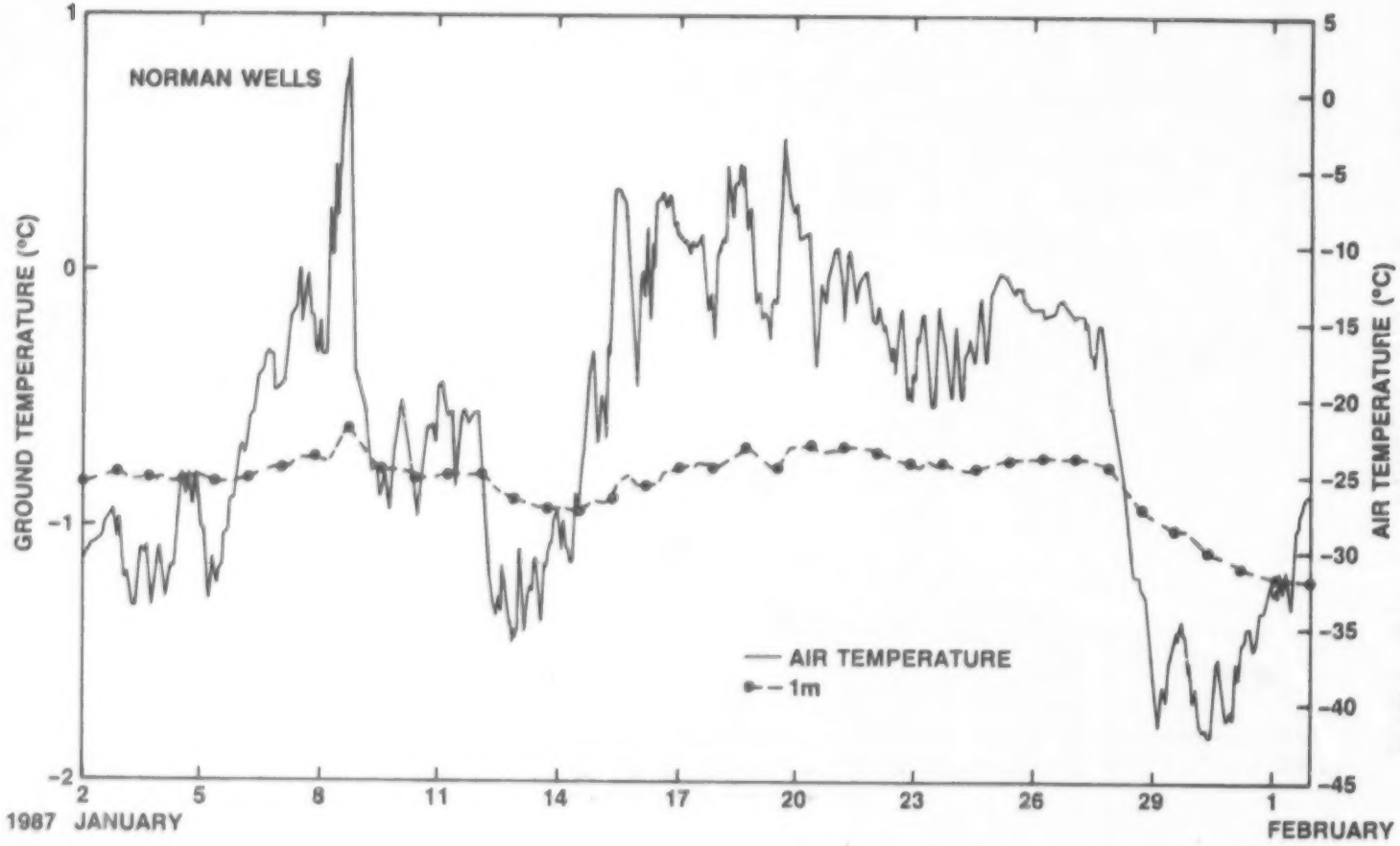
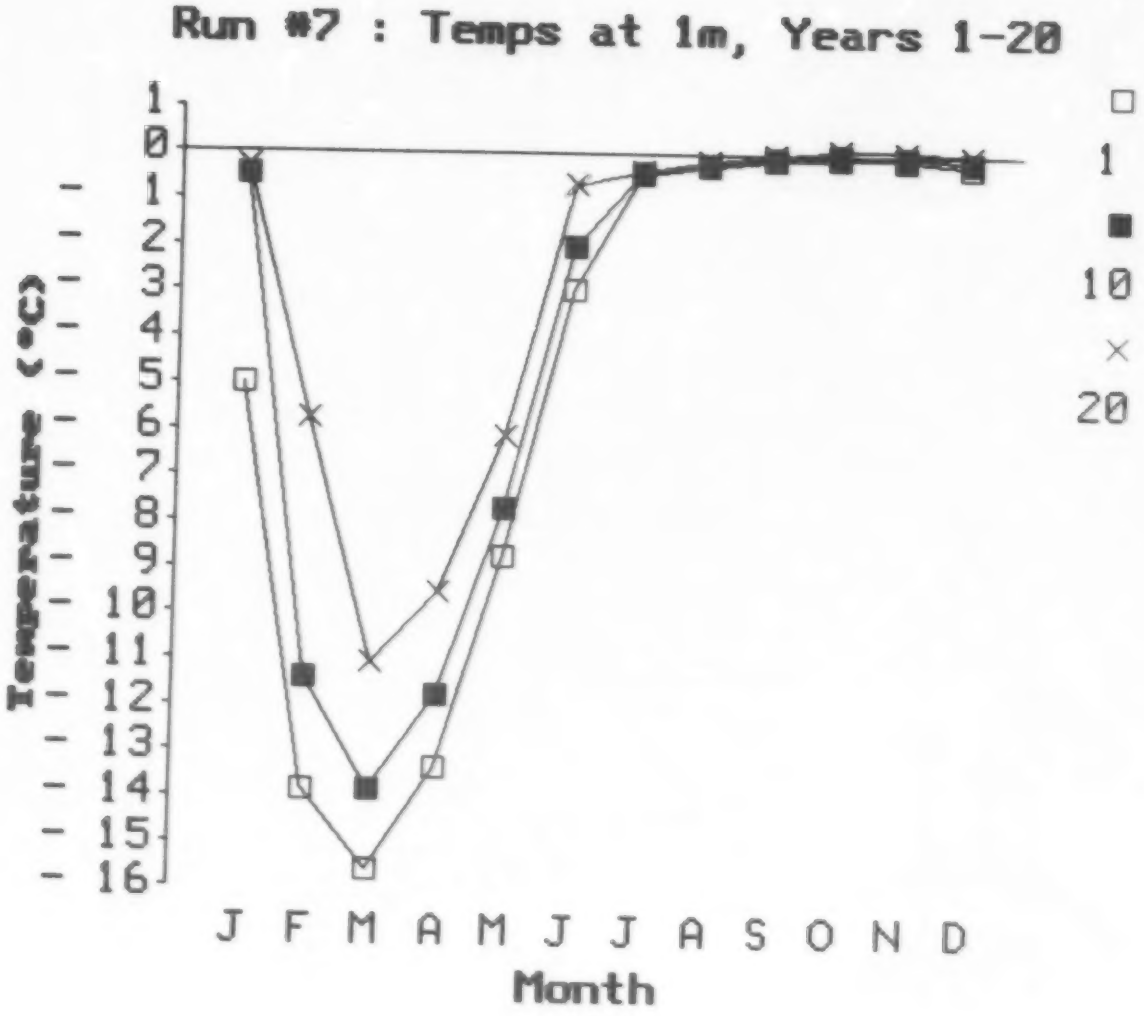
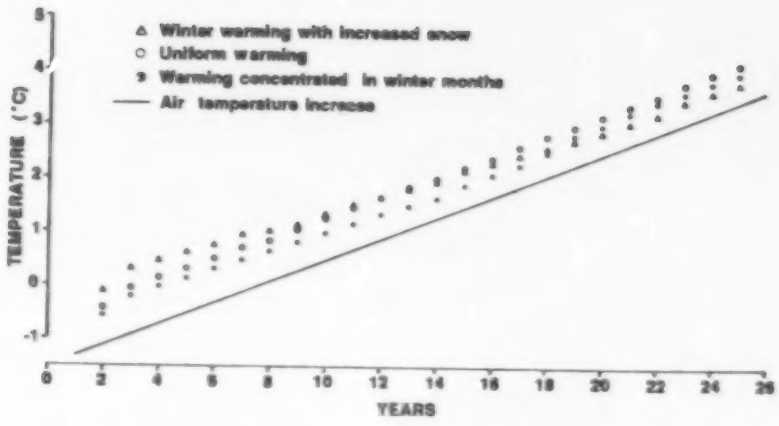


Figure 39



Ground temperature response to surface warming

Figure 40



Response of Mean Annual Ground Surface Temperature to Climatic Warming Trends.

Figure 41

APPENDIX 1

Permafrost Research:
An Assessment Of Future Needs

Committee on Permafrost
Polar Research Board
Commission on Physical Sciences, Mathematics, and Resources
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C. 1983

3
Climate, Active Layer, and Thermal Regime

INTRODUCTION

Permafrost, or perennially frozen ground, forms over a long time in response to cold climate. Climate affects permafrost through the active layer, the layer that freezes and thaws seasonally and directly overlies the permafrost. The active layer can be visualized as a boundary layer, which separates the earth's atmosphere from the underlying permafrost and in which the transport of water, solutes, gases, and the thermal flux interact in subtle and complex ways. The thermal regime in the underlying permafrost is the integrated response of climate, surface-energy exchange, active-layer processes, and geothermal heat flow.

RESEARCH NEEDS

Climate

Permafrost is nearly an ideal material for monitoring climatic changes. Because most of the pore water in permafrost is held in the form of ice, the thermal regime of the permafrost is not usually affected by pore water movement, thus allowing direct application of purely conductive heat transfer models. The great depth of permafrost at some sites in Alaska and the long time scales for response to surface temperature changes (as many as several thousand years) make it possible to study long-term changes in surface temperature produced by climatic changes.

Recent studies by climatologists demonstrate almost universal agreement that the increasing carbon dioxide

(CO_2) content of the atmosphere will be accompanied by a general warming of the earth (Manabe and Wetherald 1980; MacDonald 1982; Panel on Energy and Climate 1977; Ad Hoc Study Group on Carbon Dioxide and Climate 1979; Ad Hoc Panel on Economic and Social Implication of Increasing Atmospheric Carbon Dioxide 1980). The projections are that warming in the polar regions will be greater than in temperate regions. Present climate models suggest that doubling of the CO_2 content of the atmosphere will increase the surface air temperatures in the polar regions by roughly 3°C. Changes in the thermal regime of the permafrost that would follow warming of the air at the surface are difficult to predict. The near-surface permafrost in northern Alaska has warmed about 2°C during the last century, possibly in response to higher air temperatures (Gold and Lachenbruch 1973).

The potential effects of warming the permafrost will be different in the continuous and discontinuous permafrost zones. In the continuous zone, thaw lakes, coastal processes, eolian activity, and vegetation will be sensitive to climatic change, but the effect on the permafrost would be initially to warm it and to increase the thickness of the active layer. Other effects, such as thinning of the permafrost by thawing at its base, would require several centuries to begin.

In the discontinuous zone, the effect of a rise in mean annual temperature (MAT) at the ground surface would be increasingly serious as the MAT approached 0°C. As much of the permafrost in the discontinuous zone generally has a MAT higher than -3°C, much of this so-called warm permafrost would eventually disappear. Although many centuries would be required for relatively thick permafrost to disappear, increases in the thickness of the active layer and thawing from the top would begin to take place concurrently with the warming, so that attendant problems associated with thaw settlement and erosion would probably occur with a minimal time lag.

Differential thaw settlement may be expected to cause damage to houses, roads, airports, and other structures; to hinder farming (through thermokarst formation); to deepen and/or widen stream channels and increase sediment transport in rivers; and to increase the incidence of slope instability problems. Such dramatic changes as these have the potential for disrupting social and economic activities.

To assess and predict the extent of climatic change, the existing network of manned and automatic meteorological stations should be greatly expanded in polar and alpine regions to provide measurements throughout the year. Such expansion of the observational network will be difficult in these remote and hostile environments but should be considered in light of the value of the data that would result. Ground-surface energy-exchange components such as radiation, evaporation, convective heat exchange, and conduction and convection should be monitored. In Alaska most of the present meteorological stations are situated along the few large rivers or in coastal areas. The extensive inland and high-elevation areas should be included in the network to provide better data on the interrelationship of permafrost and climate. Measurements of climatic conditions are especially important along the southern boundary of the discontinuous permafrost zone where these conditions can determine whether permafrost is present and if it will degrade when the surface is modified. A similar paucity of data collection activities exists in the alpine regions of the contiguous United States. A related basic need is to expand mapping of snow depth, density, and water content through the winter season, including local variability because of wind and other factors.

Variations of mean annual air temperature, net radiation, mean annual ground-surface temperature, and ground temperature at depth of zero annual amplitude should be observed in relation to elevation, slope, aspect (north- and south-facing slopes), and topographic position.

Active Layer

Although by definition permafrost underlies the active layer, not all permafrost is covered by an active layer. For example, the upper permafrost surface beneath a deep freshwater lake will lack an active layer, and there will usually be no active layer above subsea permafrost, for in neither situation is there an annual thaw and freeze. The thermal regime of the active layer is a complex response to many environmental factors such as climate, material type, and topography. As the environmental factors interact in intricate ways, it is usually difficult to assess the role of any given factor, even in the relatively simple case of a homogeneous material

devoid of vegetation. The problem is much more complicated where the material is inhomogeneous and vegetation is present. Research on the active layer is an essential component of research on permafrost, because the active layer is the medium through which all surface temperature changes, whether natural or human induced, are transmitted by heat transfer into and out of the underlying permafrost. For many pile-supported structures, the thickness and freezeback of the active layer are important considerations in basic pile design. The prediction of long-term variations in the active-layer thickness therefore becomes critical to foundation design.

The active layer is a dynamic zone compared to the underlying permafrost. As a result of its annual freezing and thawing, it supports plant growth, biological activity, and soil-forming processes. Soil movement frequently takes place within the active layer. In areas of discontinuous permafrost, freezing is predominantly from the surface downward, whereas in areas of continuous permafrost, freezing can occur from both the surface and downward and upward from the underlying permafrost table. As freezing occurs, there will be moisture migration to the freezing zone(s), ice lense formation, and a concomitant water depletion elsewhere. In areas of well-drained soils, the lower active-layer and near-surface permafrost may lack segregated ice. Under these conditions, deep penetration of leachates and soil solutions can occur during thaw, and monitoring of the composition of drainage water from these sites is of considerable pedologic interest.

After the active layer has frozen through to permafrost, there is no physical distinction between the frozen active layer and the top of permafrost. However, the general direction of heat flow will reverse from upward in winter to downward in summer. Although research on the hydraulic conductivity of frozen ground under field conditions is limited, there is mounting field evidence, from a variety of international observations, to suggest that appreciable amounts of unfrozen pore water may move slowly upward from the top of warm permafrost in winter and downward through the still-frozen active layer into permafrost in summer. Research on this unusual process is best carried out under field conditions where the soils have not been disturbed, the temperature gradients are often very small, and the time period is long compared to experiments normally carried out in the laboratory. However, full-scale laboratory experiments on this ice water transfer process may be possible as experimental facilities to determine soil frost effects become available. Analyses of the distribution of tritium in the upper section of permafrost can help in studying the downward movement of water into permafrost.

Another pressing research problem relates to climatic change, both past and future. Past climatic changes can be recognized in buried soil horizons, buried ice, truncated ice wedges, buried soil microfabrics produced by repeated freeze-thaw cycles, and other indicators. A study of past evidence for climatic change should assist in evaluating future changes. A careful and systematic long-term monitoring of the active layer at selected sites seems highly desirable to assess climatically induced changes in the underlying permafrost. Long-term observations in the active layer and near-surface permafrost are difficult, for the disturbances from installation of sensors and repetitive measurements over time may alter the natural conditions, producing somewhat erroneous results.

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Thermal Regime

An understanding of the distribution of permafrost and its growth and deterioration from natural or artificial causes requires a knowledge of the temperatures beneath the earth's surface and the factors that control them. Because permafrost is defined on the basis of temperature, the most direct way of establishing its presence is to measure the earth temperature. Measurements of permafrost temperature can also be used to assess its thermodynamic state, measure the geothermal heat flux, help define the heat and mass balance, measure the position of the top and bottom of the permafrost and its thickness, determine the permafrost distribution and whether it is aggrading or degrading, help assess the presence or absence of ice, and measure permafrost properties such as the freezing-point depression of the soil water and the thermal conductivity. Further refinement of methods for measuring, interpreting, and modeling temperatures in permafrost are required. Efforts to understand and evaluate recent and future climatic changes and the effects of human activities on the environment require thermal studies of permafrost. The thermal interaction of engineering structures and permafrost must be understood to allow for proper design of these structures.

Analytical methods for calculating ground temperatures for given boundary and initial conditions and thermal properties are relatively reliable for cases of purely conductive heat flow but are not adequate for cases involving water motion and the presence of multiple phases. Solutions for problems involving phase change for a greater variety of initial and boundary conditions and geometries are needed. A number of numerical methods have been applied to permafrost problems; however, most of these are either proprietary or of limited application or still in various stages of refinement. Several numerical frost-heave models are available in the public domain; a major research effort has been directed to their improvement. Still, the effects of saline groundwater, convection, and simultaneous heat and mass transport are poorly known. These coupled processes and the thermal properties of permafrost are discussed later.

Although we have laboratory methods for the study of frozen soil, there is a pressing need for in situ methods. In situ thermal conductivity probes have been used to measure annual changes in thermal conductivity. The presence of unfrozen water (associated with soil-particle size, pressure, and the salts in permafrost) introduces uncertainties into the determination of the position and temperature of the top and bottom of ice-bearing permafrost, measurement of permafrost properties, and interpretation of the thermal regime. This situation appears to be common in subsea permafrost and in permafrost consisting of very-fine-grained materials. Convection in boreholes can also be a problem in interpreting measured permafrost temperature profiles.

More information is needed on heat flow in permafrost regions, including mountainous areas such as the Brooks Range in Alaska, especially where the heat flow is anomalously high as shown by substantial groundwater discharge and thermal springs. Where adequate data are available, different heat flow provinces should be identified and mapped.

A series of permanent stations should be established for long-term ground temperature measurements, together with meteorological measurements. These stations should cover a cross section of climatic and geologic settings.

RECOMMENDATIONS

We recommend that a modest drilling and temperature measurement program be established at a number of sites representing a variety of geological, climatological, and physical settings, including alpine permafrost in the contiguous United States. In addition, a modest drilling program should be instituted in Alaska to expand the present network of deep-temperature holes located primarily in the northern part of the state and monitored by the U.S. Geological Survey. Information from these boreholes would also be useful in further defining the distribution, characteristics, and geological aspects of permafrost in Alaska. Each year a large number of holes are drilled in Alaska by industry. The industry and regulatory and resource agencies should be encouraged, possibly through relaxation of federal and state regulations governing borehole completion, to make some boreholes (e.g., dry wells) available for the purpose of studying the thermal regime of the permafrost. Much remains to be learned concerning past climate in Alaska by studying borehole temperatures and changes in permafrost indicators (e.g.,thaw lakes, geomorphic features, ground ice). Additional research is needed to determine the magnitude of sources and sinks of CO_2 in permafrost terrain (e.g., lake sediments, peat, degrading permafrost) and to define gas transport mechanisms and rates through permafrost. New and simple methods are needed to determine the MAT at the ground surface and the amplitude of surface temperature variations in permafrost terrain.

We recommend long-term monitoring of temperatures and thicknesses of the active layer at both representative undisturbed and disturbed sites to obtain baseline data for assessing the effects of short-term and long-term climatic changes. In addition, research should continue on processes relating to upward freezing in the active layer, moisture migration, ground-surface heave, formation of microfabrics, and development of freezing potentials.

We recommend that research on the extent of the thaw zone beneath water bodies be continued in order to better understand and predict the relationship of water bodies to the aggradation and degradation of permafrost.

We recommend the continued development of analytical methods and numerical models that can be applied to permafrost problems. Models addressing the effects of surface modifications on permafrost and the interaction of engineering structures with permafrost are especially needed. Natural and artificial thermal disturbances should be used for the purpose of determining the thermal properties of permafrost. Techniques for continuous temperature logging of drill holes are needed to obtain information on lithology, presence of pore fluids, and ice content.

We recommend increased research on ways to measure temperature-dependent properties and processes in permafrost. The problem of convection in boreholes needs to be evaluated as a function of borehole size, casing type, fluid viscosity, and thermal gradient. New and improved experimental methods are needed for determining the position of the top and bottom of ice-bearing permafrost and for in situ measurements of permafrost properties, especially in the presence of unfrozen pore water.